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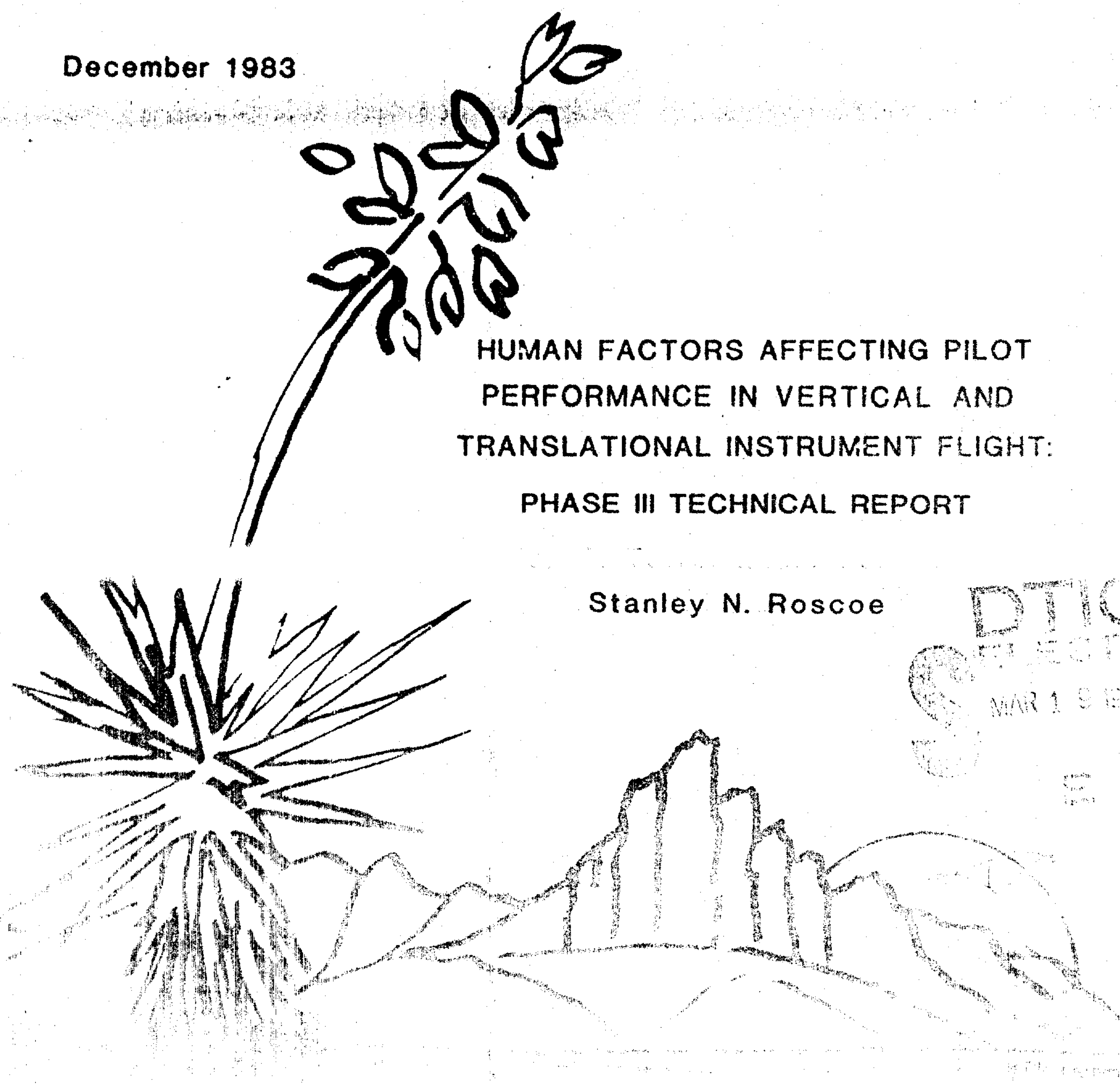

HUMAN FACTORS AFFECTING PILOT PERFORMANCE IN VERTICAL AND TRANSLATIONAL INSTRUMENT FLIGHT: PHASE III TECHNICAL REPORT

Stanley N. Roscoe

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As part of an overall research program to develop both forward-looking and downward-looking tactical situation displays for all-weather instrument flight in VTOLs, an integrated horizontal situation display was developed for both vertical and translational flight. This report covers the development and initial experimentation of the downward-looking display and control system. The effects of eight factors on pilot performance were tested, and multiple regression models of VTOL pilot performance as a function of those eight factors were derived for each of three dependent performance measures.

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ACRONYMS

AGB	Altitude goal bar
AGL	Above ground level
AHA	Altitude hold autopilot
AHF	Altitude-hold function
BEL	NMSU's Behavioral Engineering Laboratory
CG	Control gain
CO	Control order
CTOL	Conventional takeoff and landing
DVR	Desired vertical rate
GPS	Global Positioning System
GR	Altitude gain reduction logic
HOVERING	HOrizontally and VERtically INteGrated
HSD	Horizontal situation display
HSI	Horizontal situation indicator
ILS	Instrument landing system
IP	Initial position error
MF	Magnification factor
PO	Prediction order
PT	Prediction time
RHF	Rate-hold function
SID	Standard instrument departure
TACAN	Tactical air navigation
TM	Tracking mode ($\neq$ VRC)
TRC	Target-referenced compensatory

TRHF	Translational RHF
VAI	Vernier altitude indicator
VDI	Vernier deviation indication
VOR	Very-high-frequency omnidirectional radio
VRHF	Vertical RHF
VRC	Vehicle-referenced compensatory
VRI	Verticle rate indicator
VSC	Vertical speed control
VSD	Vertical situation display
VTOL	Vertical takeoff and landing

INTRODUCTION

Context

Currently the operational potential of vertical takeoff and landing (VTOL) aircraft that are controlled by vectored engine thrust (e.g., AV-8A Harrier) can not be exploited in bad weather or at night. Helicopters, on the other hand, do have instrument flight capabilities, although pilot workload tends to be undesirably high. In contrast, conventional takeoff and landing (CTOL) aircraft have been operating in poor weather and at night for many years. This seems paradoxical since VTOL aircraft can land on any reasonably flat spot, can stop quickly if necessary, and are inherently more maneuverable than CTOLs. Despite all these performance advantages, VTOLs have not yet achieved operational capability under all-weather conditions.

Sources of the VTOLs' current inability to operate in minimum visibility can be divided into two major categories: (1) inadequate control stabilization (Ringland, 1977; Roscoe & Bergman, 1980; Wellern, 1971), and (2) inadequate instrumentation (NATO, 1972; Roscoe, Hull, Simon, and Corl, 1981). The heart of the instrumentation problem with both VTOLs and helicopters has always been the instabilities inherent in conventional control systems. Any realistic hope of achieving the vertical and translational maneuvering potential of these aircraft must start with the adoption of control systems that provide direct maneuevering performance control (Roscoe & Kraus, 1973).

Recent advances in control augmentation have made the implementation of performance control systems in VTOLs near-state-of-the-art (Vaccarino, 1982). Through the use of the NAVSTAR satellite global positioning system (GPS) in combination with inertial smoothing, vehicle positions, rates, and accelerations can be obtained quite accurately. Data from the inertial sensing system (whether conventional or strapdown) are filtered or smoothed and then integrated with onboard microprocessors. With the appropriate software, these systems are capable of providing stabilized heading and attitudes as well as reduced orders of control.

As the control stabilization problem is resolved, it will become readily apparent that what is required for all-weather operational capability in both VTOLs and helicopters are integrated forward-looking and downward-looking presentations of the horizontal and vertical positions, rates, and accelerations of the vehicle relative to the external world. The focus of this research is on the downward-looking portion of the overall display system.

Advances in avionics technology have permitted a variety of new applications for future aircraft instrumentation (Lerner, 1983; Roscoe, Corl, and Jensen, 1981). These advances in avionics capabilities, especially the explosion in low-cost, light-weight, and highly reliable computing and display technology, have made possible the implementation of good old display ideas that were once impractical. This research will integrate several dimensions of the current state-of-the-art in avionics and demonstrate their applicability for future VTOL instrumentation development and potential.

The quest for general rules or principles that describe, predict, and ultimately explain skilled performance often can be facilitated by constructing an analog or conceptual model. In 1947 at the University of Illinois, Professor Alexander Williams undertook an analysis of the information pilots need for instrument flight. Williams (1947; 1980) conceived a basic model involving the mission's goal (G) and hierarchical subgoals (SGs)--the specific indices of desired and actual flight performance--all embedded in the context of the immediate flight environment--the physical facts of flight (PF). Subsequently, Carel (1965) and Roscoe (1968, 1974, 1980) have advanced Williams' concept as it appears in Figure 1.

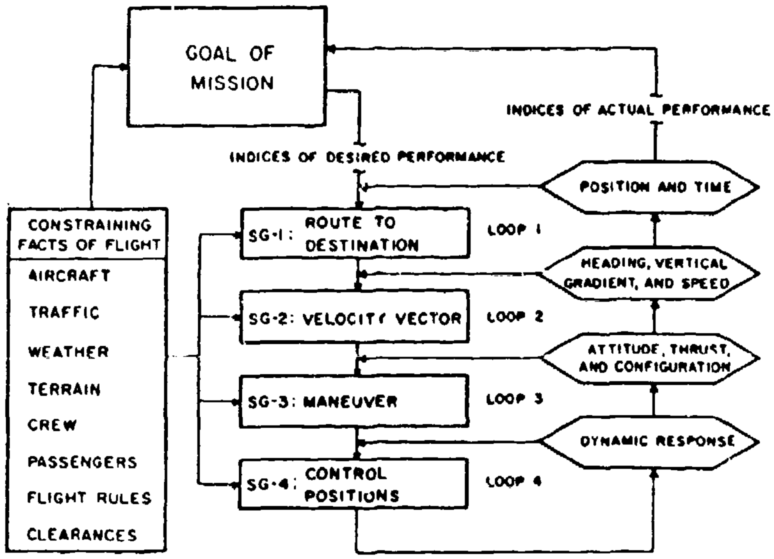


Figure 1. Hierarchical nature of the flight task (Roscoe, 1980).

Quoting Roscoe (1980, 5-6):

> A flight mission, like any human activity, is goal directed. Planning starts with the assignment or self-selection of the goal, after which the pilot selects the various subgoals that will lead to the accomplishment of the mission. Thus the pilot has to determine --moment-to-moment throughout a flight--the altitude to fly, the heading to fly, the speed to fly, how long to fly, and the operating condition of the aircraft

and its subsystems. Because the control of an aircraft is hierarchical in nature, as indicated in the conceptual model, flying is complicated by the several necessary transformations between what the pilots sees and hears and feels and how [illegible] move the controls at the lowest loop in the hie[illegible]y.

If the relationships between the constraining conditions of flight, the indices of desired performance, and the control of actual aircraft and subsystem performance were simple, there would be little for pilots to do; but they are not simple, and the analysis of the transformations that pilots must make in performing a given mission defines not only the information they must receive from flight instruments or the outside world but also the things they must do with that information to control an airplane sucessfully.

Making these transformations is difficult, at best, if the hierarchically related items of information are presented individually in separate instruments having various formats. Development of an integrated display system is essential to reduce the number of transformations required in current VTOL display configurations. In our current quest for general rules for the compatible integration of guidance and control functions in helicopters and other VTOL craft, we have taken this hierarchical model of the pilot's flight task as the basis for the allocation of functions to pilot and computer and for the organization of information presentation for vertical and translational instrument flight.

Williams viewed the basic flight task (whether performed by pilot or computer) as the linking of discrimination and manipulation events involving the iterative asking and answering of four questions:

1. What shoul[illegible] my route to my destination, and where am I with respect to my desired route and destination?

2. What should be my velocity vector, and what is it now?

3. What should be my altitude, thrust, and configuration, and what are they now?

4. What should I do with the controls to correct discrepancies that may exist in 1, 2, and 3?

An integrated display and control system should present the information necessary for the pilot to answer these hierarchically related questions

quickly and accurately throughout a mission. We interpret this requirement to imply that hierarchically related information should be organized for display in an analagous manner. Starting at the top, we take it as a given that the pilot, not the computer, is in command and, in conjunction with gound-based authority, is responsible for route-to-goal selection, subject to computer monitoring to preclude unsafe or impractical selections. From bottom up, we expect the computer to relieve the pilot of routine manipulation of the aircraft's dynamic responses, subject to pilot monitoring and intervention when needed.

Thus, in typical operations the pilot's action responsibilities will decrease and the computer's will increase from top down, whereas their respective monitoring authorities will progress inversely. These divisions of responsibility and authority impose requirements on the pilot's displays and controls that in turn guide us in selecting the most applicable design principles. Because the pilot's primary responsibility is course-of-action selection, a "big picture" of the tactical situation is needed, but because the pilot may be called on to enter the bottom, or inner, control loop in an emergency (with little routine practice), stabilization through control augmentation and sensitive, directionally compatible tracking error indications are also required.

The problem becomes one of finding mutually compatible solutions to the simultaneous presentation of answers to all four questions listed above, taking into account emergency as well as routine action requirements of the pilot. This accomplishment will require the implementation of several basic display principles in both forward-looking and downward-looking tactical situation displays. To do this, instrumentation must provide the pilot with information from each level of the flight task hierarchy: the positions of relevant aspects of the external environment (implementing the necessary transformations between questions 1 and 2); superposed representations of the planned or authorized flight profile and projections of present performance (questions 2/3); and magnified indications of instantaneous deviations from the indices of desired performance (questions 3/4).

Background

Horizontal situation displays (HSDs) are downward-looking projections of information about an aircraft's position relative to the horizontal plane beneath the aircraft (Quinn, 1982). HSDs usually provide navigational and/or tactical aids, depending on mission requirements. Specific information provided by most HSDs includes: target and threat symbology, waypoints, VOR and TACAN information, course lines, deviation from desired course (and flight path prediction in some cases), time and distance to destination, heading, and sometimes projected maps (Figures 2-5). Only a few attempts have been made to integrate navigational information with other vital flight information in an HSD (Dukes, 1970, & 1974; Roscoe, Hull, Simon, and Corl, 1981). In the case of helicopters and other VTOL aircraft and CTOLs during certain mission phases (e.g., terrain following), not only is navigational aid important, but information regarding altitude control is also critical.

Although several researchers (see Quinn, 1982) have developed VSDs capable of providing the necessary information for altitude control (NIAC) and forward rate control (NIFRC), in no case has NIAC been truly integrated in an HSD. VTOLs perform a variety of missions that require not only precise translational control, but accurate and stable control of altitude as well. These flight tasks combined with other station-keeping tasks lead to undesirably high cockpit workload in VTOLs during both contact and instrument flight. Numerous researchers have shown the value of integrated flight displays in reducing cockpit workload and procedural blunders (Banbury, 1980; Jones, 1980; Payne, 1952; Prince, 1980; Roscoe, Johnson, Dittman, and Williams, 1950; Roscoe, 1980; Simon and Roscoe, 1956; Waller and Logon, 1981; Williams and Roscoe, 1949).

In the case of VTOLs, mission requirements often burden the pilot with both precise translational and altitude control. For example, the approach and subsequent hover prior to a shipboard landing in a VTOL require both precise translational and vertical control. Translational control is relatively critical during the approach, but it is most critical during the hover phase prior to touchdown, whereas altitude control is critical throughout all landing phases. These include glideslope intercept, decelerating descent to a specific altitude above ground level (AGL) prior to flare, flaring the aircraft (i.e., transition from aerodynamic to thrust-borne flight), approach to hover, hover, and descent to touchdown. Workload during landings of this sort becomes extremely high (Bode, Kendrick, and Kane, 1979), and this burden, in part, can be attributed to inadequate instrumentation and lack of display integration.

Current HSDs in VTOLs provide information for navigation and translational control only, while NIAC is left to conventional altimeters, rate of climb indicators, and radar altitude digital displays (all of which are separate presentations). A highly trained, skillful pilot is only marginally capable of scanning an HSD and various altitude indicators to make good precise flight paths while maintaining desired altitude during instrument flight in VTOL aircraft. However, because these requirements are usually only a small portion of the pilot's overall mission, full attention cannot be

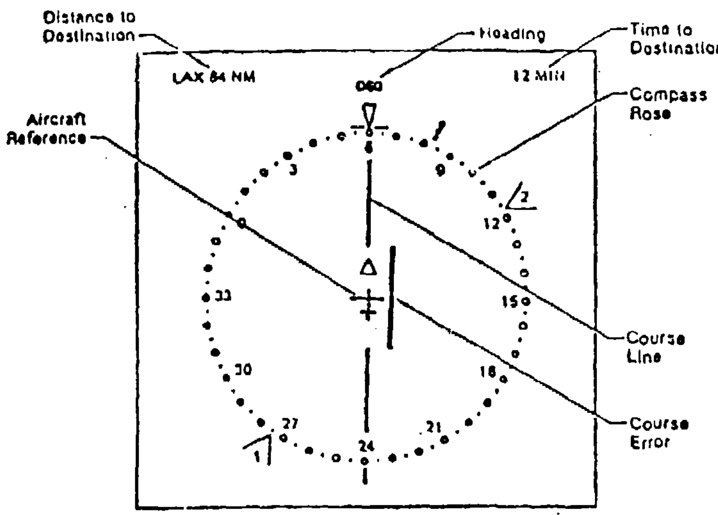


Figure 2. Electronic horizontal situation indicator (EHSI) with vehicle-referenced compensatory tracking, displaying present location (left of course), time and distance to destination, heading, and rotating compass rose (Willich & Edwards, 1975).

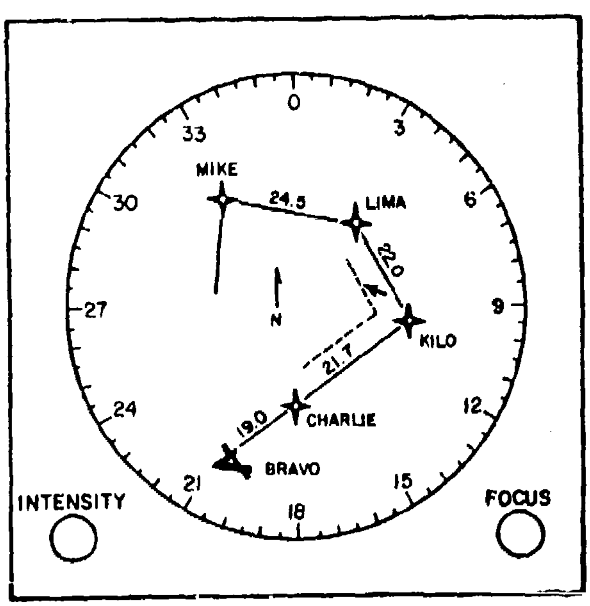


Figure 3. Computer-generated map display showing aircraft position (arrow) relative to a 5-mile left offset from a Standard Instrument Departure (SID) route (Roscoe, 1980).

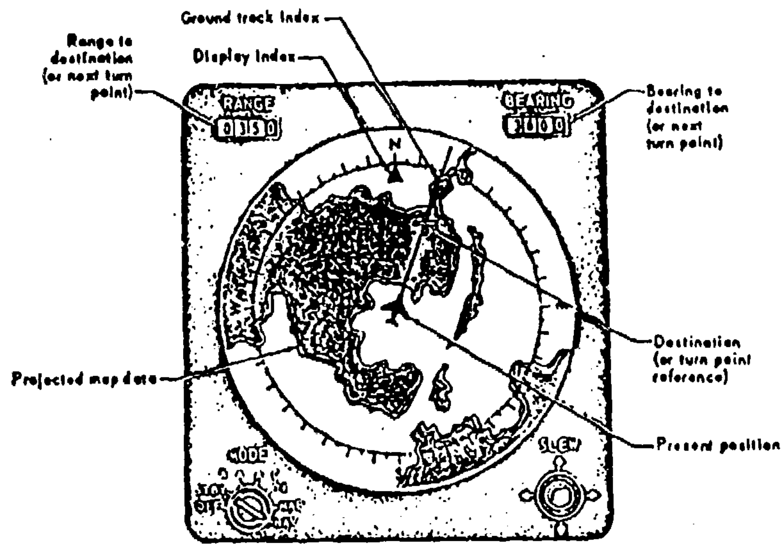


Figure 4. Multipurpose-navigation display in projected map mode. Present position is indicated by aircraft position over projected map. Range, bearing, ground track, and destination are also indicated (Shrager, 1974).

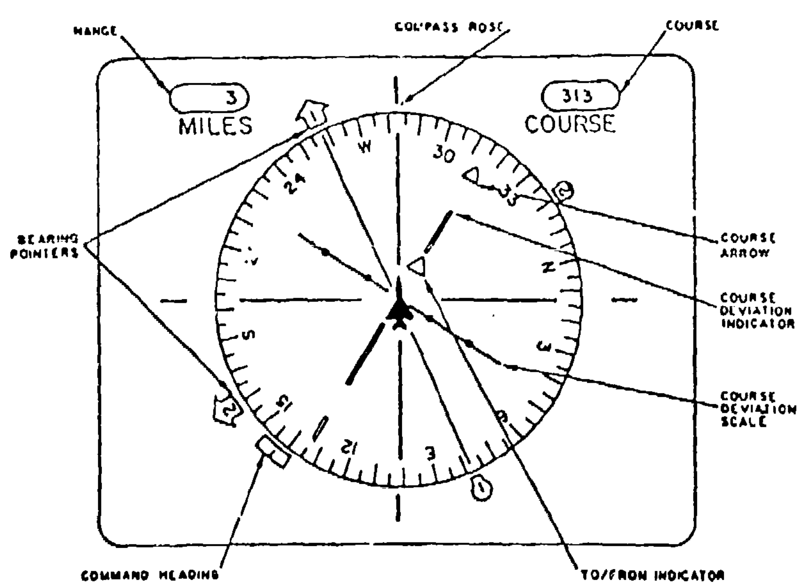


Figure 5. Horizontal situation display with vehicle-referenced compensatory tracking. Range, present and desired course, bearing, command heading, to/from VOR indication, and rotating compass rose are included (Snyder, 1980).

devoted to translational and vertical control. Various station-keeping duties, systems monitoring, communications, and target detection tasks increase cockpit workload in VTOLs well beyond manageable levels.

Improvement of present instrumentation (e.g., optimization of navigational information presented on HSDs) and advances in display integration combined with control augmentation are necessary steps toward realization of all-weather instrument flight for VTOLs. HSDs not only must be optimized for translational control, but NIAC must also be integrated into HSDs. There are a few problems that do arise when considering the integration of additional information into an existing or developing HSD. The additional information must be presented unambiguously, and it must also be done in such a manner as to avoid excessive display clutter.

A few researchers, most notably Dukes (1970), have attempted to develop an HSD capable of providing both navigational aids and other critical flight information while avoiding unnecessary display clutter. The systematic development of Dukes' display was based on several display principles that are generally accepted as crucial by most operational personnel in the field (although there may not be consensus on the proper terminology to describe these principles). The principles are: (1) fully integrated multivariable information, (2) systematic arrangement of derivative information, (3) true deviation display, and (4) compatible control motion arrangement.

Dukes described a fully integrated multivariable information display as one that reduces scanning and fixation losses to a minimum. Also, all of the necessary information to make good a desired flight path must be provided in an integrated manner such that additional information is not required for a pilot to perform all the necessary loop closures required during flight (see Roscoe, 1980, p. 5-6). A display must present true deviation information. This requires the concurrent presentation of desired position and rates as well as actual position and rates, again, in an integrated fashion. And finally, the display must present accelerations, error rates, and position errors such that they exhibit control/display direction of motion compatibility and are interpreted easily and naturally.

Dukes' investigation provided evidence that the development of an HSD that integrates both navigational aids for translational control and NIAC is feasible and makes possible all-weather instrument flight in VTOLs. His HSD consisted of several desirable features in an integrated HSD or any display. His display was developed such that control and display dynamics are directionally compatible. He also provided flight prediction in both the horizontal and vertical dimensions, which is known to reduce tracking errors considerably (Poulton, 1974; Roscoe and Jensen, 1981).

Dukes' approach represents a positive step toward the development of an HSD capable of unambiguously presenting both navigational and flight control aids. In fact, with such a display instrument flight could conceivably be safer than contact flight. Before this objective is achieved, however, several display design problems must be surmounted. For example, NIAC must be integrated with the horizontal presentation while maintaining compatible display/control motion relationships. This is a considerable problem on a two-dimensional surface. In Dukes' display this problem was

circumvented by presenting NIAC in a nonintegrated format along the side of the HSD. This did have the effect of reducing scanning time, but presenting NIAC in an integrated fashion is the objective.

DEVELOPMENT OF A HORIZONTALLY AND VERTICALLY INTEGRATED HSD

The initial development of a display necessitates the specification of its operational requirements. In the case of the display reported here, it must allow stable, accurate, and safe operation of a VTOL aircraft in zero visibility conditions. An extensive literature review was conducted by researchers at NMSU's Behavioral Engineering Laboratory (BEL) to determine information requirements for all-weather instrument flight in VTOL aircraft (Roscoe et al., 1981). It was concluded that VTOL mission requirements can be satisfied by the combination of a forward-looking vertical situation display (VSD) and an HSD that integrates navigational information for translational control with altitude and vertical rate information for vertical control.

Display Principles

As was the case with Dukes' display development, a number of basic display principles that have been empirically tested and supported were applied to the development of the prototype HSD. These display principles include: (1) pictorial realism, (2) error magnification, (3) display integration, (4) compatible motion, (5) frequency separation, and (6) flight-path prediction (Roscoe, Corl, and Jensen, 1981). Although some of the concepts underlying these display principles are redundant with those employed by Dukes, some have been overlooked or simply not applied to existing and developing cockpit instrumentation. This lack of display principle implementation at an operational level warrants reiteration and extension of those display principles previously mentioned.

Pictorial realism. A display that has the quality of pictorial realism is one that represents a spatial analog of the real world (Roscoe and Eisele, 1980). This principle is most often thought of in the context of so-called "contact analog" displays, but its underlying notions are applicable to displays in general. If not directly analogous to the real world, a display should be designed to give the interpreter an idea of what the "big picture" is. That is to say, the display must present information that allows inferences to be formed regarding the real world even though their presentation may not be explicit. This requires the presentation of desired instantaneous and future goals concurrently with actual vehicle performance.

Error magnification. The principle of display magnification is also most often thought of in the context of contact analog displays, but it is also an important consideration in other display contexts. Dukes (1970) used this principle implicitly when he recognized the importance of screen scale on his HSD. By using a large screen scale (i.e., a small area of the real world represented on the display), a pilot is able to make fine discriminations that allow more accurate tracking. A smaller screen scale (covering a larger area) gives the pilot a better idea of the "big picture," but at the cost of less accurate tracking. Thus, a tradeoff exists between the presentation of the big picture and display magnification with respect to tracking error (Figure 6). Whether a display is biased in one direction or another is of course a function of mission requirements. However, an optimum display would somehow present the pilot with the big picture while still preserving the necessary

sensitivity to allow accurate tracking.

Display integration. The third display principle involves the concept of display integration. A display is said to be integrated if it provides the necessary information to allow a pilot to close all of the hierarchically related flight-control loops to make an appropriate control response. All of the variables required to make good a desired flight path must be presented together in one display in a coherent fashion. This requires the careful

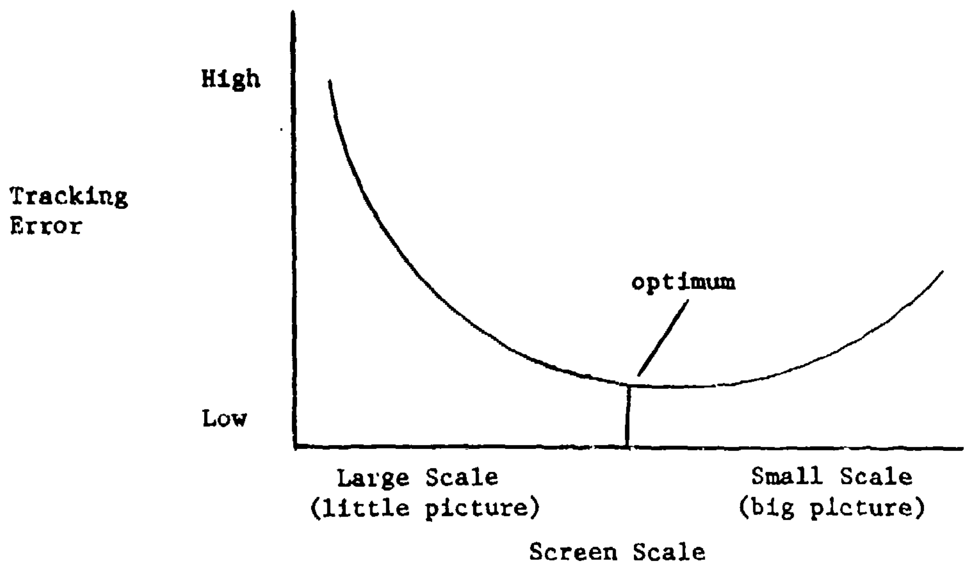


Figure 6. Tradeoff in tracking accuracy between display magnification and minification.

consideration of the point of view represented in the display and the mode of information coding (e.g., direct analog versus abstract symbology; Roscoe and Eisele, 1980).

Compatible motion. The fourth display principle involves the relationship between control inputs and a display's dynamics. When a control input is executed, the symbol representing that control's affect on the vehicle must move in the direction expected, ideally in the same plane and direction as the control movement. For example, when an aileron control is rotated to the right, an appropriate attitude display should indicate the airplane rolling clockwise. If proper display/control motion compatibility does not exist, control reversals (i.e., moving controls to increase rather than decrease error) will occasionally occur, and if not caught and corrected instantly, can be devastating during critical phases of flight.

Frequency separation. Closely related to the notion of display/control motion compatibility is the concept of frequency separation. Fogel (1959) developed a kinalog display with the intention of making displayed attitude information more compatible with kinesthetic and vestibular cues. By having the airplane symbol respond quickly and in the expected direction to initial control inputs (high-frequency responses) and then having the horizon respond more slowly in the opposite direction (low-frequency responses), he hoped to inhibit pilot control reversals. Following from Fogel, a number of researchers have demonstrated the utility of separating high-frequency reponses from low-frequency responses in the form of a frequency-separated display (Beringer, Williges, and Roscoe, 1975; Ince, Williges, and Roscoe, 1975; Roscoe and Williges, 1975).

Flight-path prediction. The final display principle is that of flight-path prediction. Flying with conventional instruments requires the pilot to differentiate rates and accelerations and then integrate those discriminations for proper control responses. Once a control input has been initiated, the pilot must predict its outcome. An effective method of assisting pilots in this task is to incorporate flight-path prediction into a display. With indications of the predictable effects of a control input to some time in the future, pilots see a priori the effects of a given control input and can correct erroneous inputs before the aircraft has made a perceivable deviation from a desired response (Figure 7).

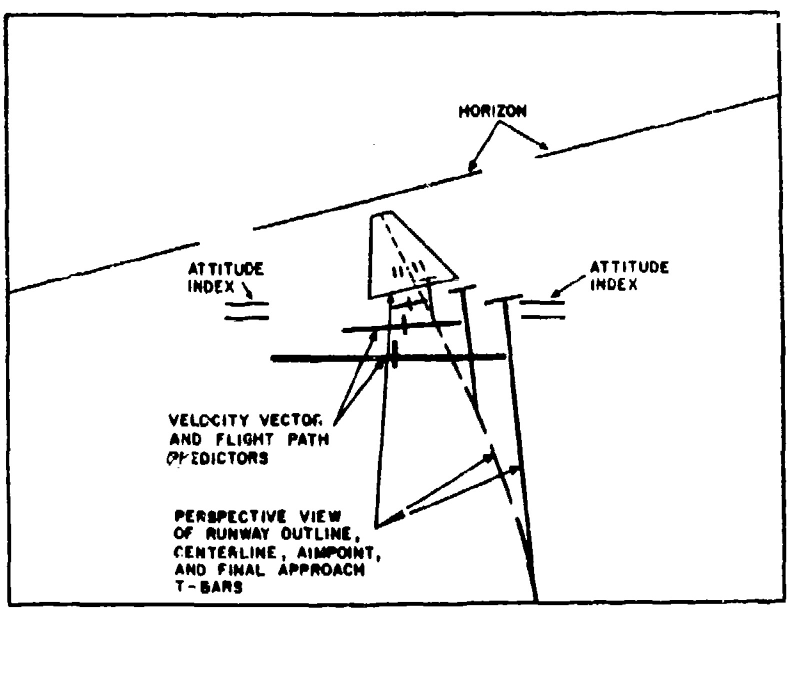


Figure 7. An example of a flight-path predictor display used for landing (Roscoe, Corl, and Jensen, 1981).

Prototype HOVERING Display

Based on the operational and informational requirements of VTOLs in conjunction with the basic display principles, a prototype display was developed at New Mexico State's Behavioral Engineering Laboratory that provides HOrizontally and VERtically INteGrated (HOVERING) position and rate information in all three spatial dimensions (Figure 8; Roscoe et al., 1981). The prototype HOVERING display provides both lateral and longitudinal error information (relative target position and own position prediction) for horizontal tracking control, a x10 vernier deviation indication (VDI) of horizontal error from instantaneous desired position, a rotating compass rose, present altitude indicator (PAI), vernier altitude indicator (VAI), and both vertical and translational rate indicators.

In both translational and hovering flight, horizontal course deviations in tracking are shown by a vehicle-referenced compensatory presentation. The vehicle is the pilot's point of reference and is always located in the center. The target (i.e., hover point or desired momentary position on flight path) is seen as a cross, and error is displayed by deviations of the target cross from the center (see Figure 8). When position error is reduced below a "magnification region" specified in screen coordinates, a x10 VDI of horizontal error is displayed. This magnification of horizontal error enables precise lateral and longitudinal control of the vehicle.

In the BEL MicroGraphic VTOL Simulator, lateral and longitudinal translational rates and/or accelerations (depending on the mode in effect) are controlled by a three-axis, spring-centered control stick mounted on the right-hand arm rest (see Figure 9). Lateral translation is controlled by left and right stick displacement from a center detent, and longitudinal translation by fore and aft stick displacement from the detent. Rotating (twisting) the stick about its vertical axis controls the vehicle's yaw (crab) angle relative to the horizontal velocity vector. The generic vehicle simulation is described in Appendix A.

The vehicle's heading in the horizontal plane is displayed by a rotating compass rose that responds to both lateral control inputs and weather-vaning of the vehicle due to the effects of relative wind. A turn-rate index line is shown relative to top-dead-center of the display so that a desired heading can be captured by matching this index with the desired position on the rotating compass rose. Longitudinal and lateral rates and accelerations are displayed indirectly by a position predictor, the computation of which depends on the mode of operation in effect.

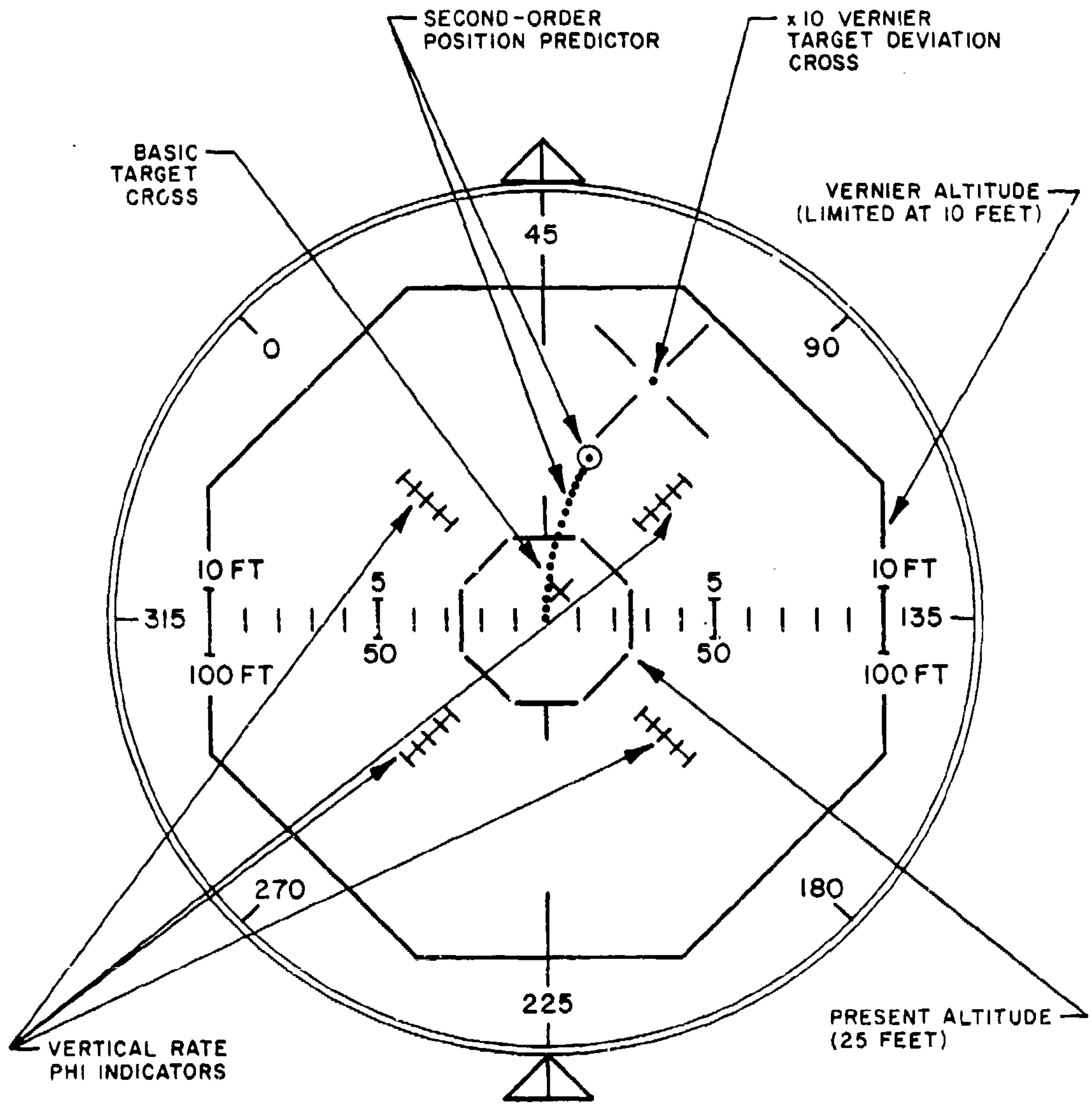


Figure 8. BEL's prototype HOVERING display developed for translational and vertical control in VTOLs during all-weather instrument flight (Roscoe, et al., 1981).

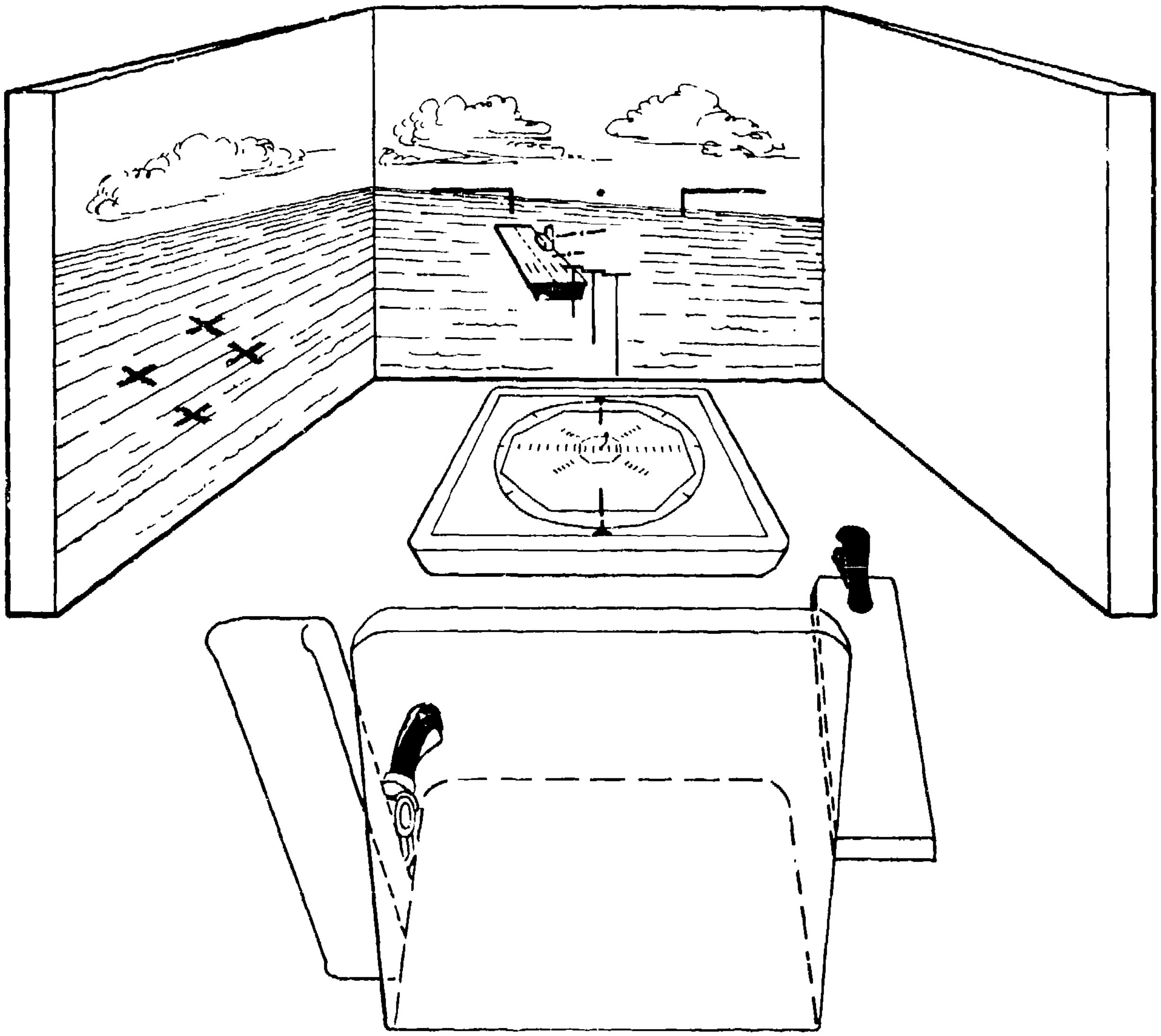


Figure 9. Configuration of BEL's MicroGraphic VTOL simulator, including the centrally located HOVERING display.

For vertical flight control, the information provided by the HOVERING display includes a present altitude indicator (PAI), a vernier altitude indicator (VAI), and vertical rate indicators (VRI). The present altitude indicator is an octagon that dilates and constricts with changes in altitude and is read at either side of a fixed scale that emanates laterally in each direction from the center of the display. The VAI is a second octagon that appears at its maximum size at 10 feet above ground level (AGL) and constricts to a point in the center of the display at ground level. The converse occurs for ascents from ground level. Vertical rate (VRI) is indicated by four sets of bars (rate fields) that flow inward to display rate of descent and outward to display rate of climb.

Vertical flight is regulated by a vertical speed control (VSC) operated by the pilot's left hand. The VSC is viscously damped and spring-centered and is operated by displacing the stick upward for climb and downward for descent. The spring-centered neutral position engages an altitude-hold function (AHF), but only when vertical rate is equal to or less than 10 fpm. This feature was necessary so engine thrust would not be violently affected if stick position were inadvertently neutralized during climbs or descents at rates greater than 10 fpm.

The HOVERING display has several desirable features in display/control relationships for translational position and rate control. A target or desired flight path is acquired by placing the predictor on the target cross using control inputs from the three-axis side-arm control. Although the display is basically an inside-out presentation, the display has frequency-separartion characteristics analogous to those developed by Roscoe and Williges (1975) for aircraft attitude indicators. The predictor functions as an immediate indication of control inputs (high-frequency responses), whereas the closure of error between target and the pilot's point of reference responds more slowly (low-frequency responses). Once a target has been acquired, the predictor should be kept on the target cross as it moves toward the pilot's point of reference.

The various features of the VSC coupled with the HOVERING display provide unprecedented display/control motion compatibility in presentations of NIAC on a horizontal surface. The dilating and constricting octagonal altitude indicator functions not only as a pointer against a fixed altitude scale, but as a peripheral indicator of vertical direction of motion. The rate-field indicators display vertical rate information in a conspicuous manner without adding unnecessary display clutter or requiring time-sharing between separate displays. This allows a pilot to "stay ahead of the airplane," which is necessary for adequate flight path precision (Swartzendruber and Roscoe, 1980).

The VAI allows precise vertical control near the surface. Presentations of this sort have proved quite effective in other contexts such as lead-collision air-to-air weapon delivery in which a circle appears at 20 seconds before firing and constricts linearly to a point at the instant of firing. The constriction of the circle serves to indicate to the pilot the need for tighter and tighter steering as the firing point is approached. In an analogous way, the VAI is an indication to the pilot that tighter and tighter control is needed as a VTOL approaches a touchdown or desired hover altitude.

The prototype HOVERING display combined with its unique flight control system represents another step toward the goal of all-weather flight capabilites in VTOL aircraft. The display provides several solutions to problems of advanced display development, general problems of display integration, and problems associated with display/control motion relationships. Optimization of the HOVERING display and control system, combined with significant advancement in inertial control stabilization technology, will provide a firm basis for the development of an operational display and control system necessary to allow stable, accurate, and safe operations of VTOL aircraft during all-weather flight conditions.

INITIAL PRETESTING AND AUGMENTATION OF THE HOVERING DISPLAY AND CONTROL SYSTEM

Extensive preexperimentation was conducted with the HOVERING display to identify both the important design variables for testing and the specific experimental levels of those variables. During this initial pretesting phase it became apparent that a few changes and augmentations would be needed in the HOVERING display and control system. Discussion of those specific changes will be necessary before describing the experimental variables and their levels that were selected for formal investigation. The following changes and augmentations were incorporated:

1. An indication that the altitude-hold function (AHF) is engaged.
2. The addition of both translational and vertical rate-hold functions.
3. The addition of explicit indications of desired vertical rate and desired instantaneous altitude.
4. A more precise means for indicating that hover altitude has been achieved.
5. A better means of presenting the "big picture" for navigational and tactical flight planning while still preserving the necessary sensitivity (magnification) to allow precise tracking.
6. Development of control system laws to increase tracking accuracy and decrease pilot workload.

Incorporation of these augmentations into the prototype HOVERING display involved once again the application of the basic display principles that were previously discussed. Integrating this additional information into the prototype HOVERING display required careful consideration of existing symbology, analysis of new symbology (in light of basic display principles), evaluation of possible consequences of increased display clutter, and considerations of display writing limitations inherent in the existing display hardware. Of course these considerations are not mutually exclusive and therefore required concurrent analysis and evaluation.

The augmentations developed for the HOVERING display for vertical flight control are illustrated in Figure 10. Desired vertical rate (DVR) information was added to the display by superposing DVR rate fields on the existing vertical rate indicators. This addition caused virtually no increase in display clutter and only a small increase in display writing time. Also, maintaining a desired vertical rate was reduced to a basic pursuit tracking task. A pilot is required to match actual VRI motion with the DVR's motion. Desired instantaneous altitude information was provided by the addition of altitude goal bars (AGBs). Similiar to the present altitude indicator, the

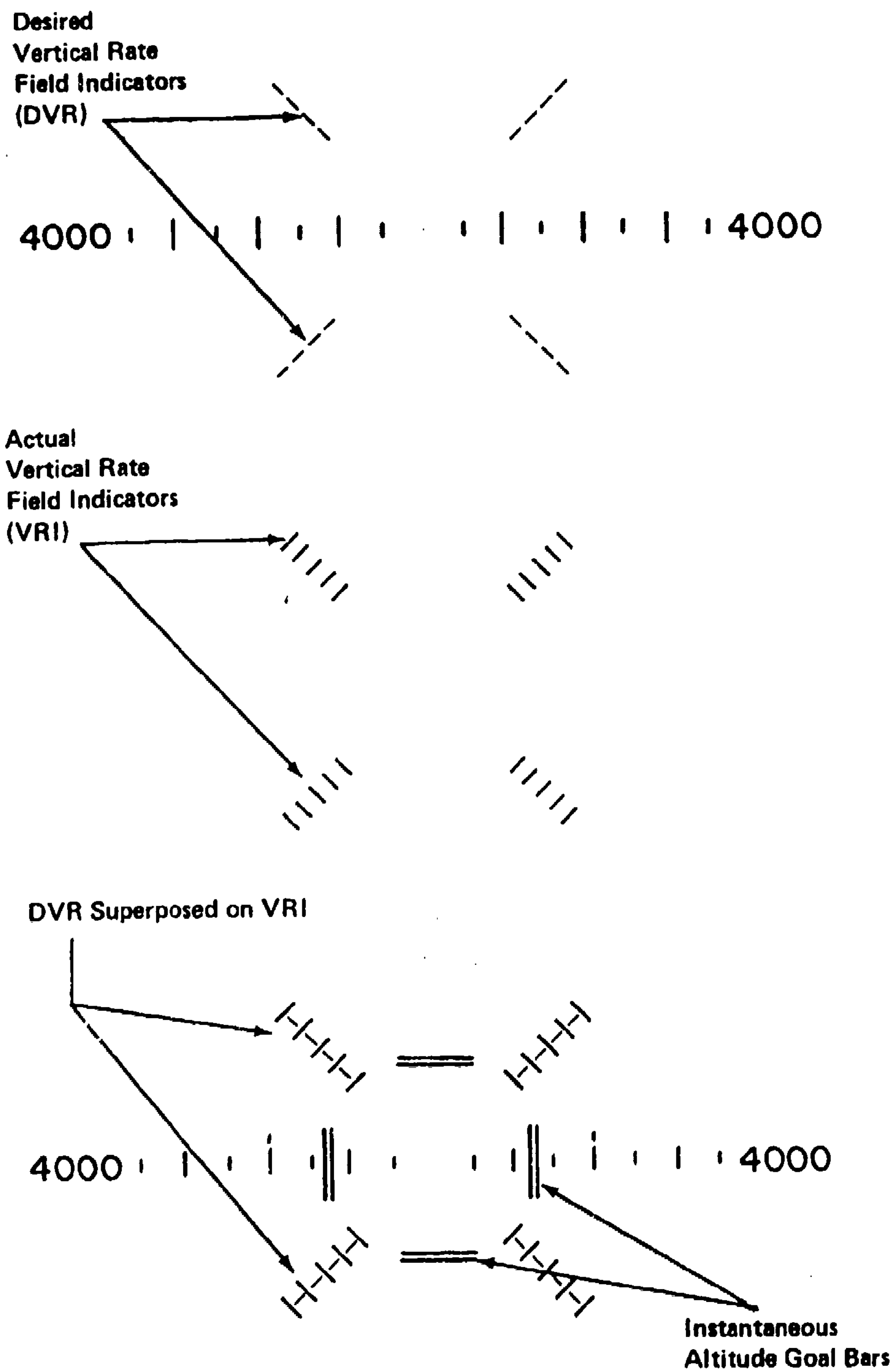


Figure 10. Augmentation developed for the HOVERING display for vertical flight.

AGBs dilate and constrict to indicate changes in desired altitude. Once again, maintaining desired altitude is reduced to a pursuit tracking task.

Pretesting of the HOVERING display revealed the need to provide the pilot with an indication that the altitude-hold function (AHF) is engaged and an unambiguous indication that hover altitude (this includes constant cruise altitude) has been achieved. Engaging the AHF requires a vertical rate of $\pm$ 10 fpm or less and the VSC to be in the center detent position. Once the AHF is engaged, the VRI and DVR indicators provide no additional information to the pilot, and thus their presentation and meaning can be altered to provide the pilot with other necessary information without additional display clutter.

The VRI and DVR indicators were altered to flash on and off repeatedly to signal the pilot that the AHF is engaged (whether intentionally or not) but that hover altitude <u>has</u> <u>not</u> been achieved. The proper response in this situation is to resume manual control and climb or descend until the required hover altitude is achieved and then reengage the AHF. Once the pilot has engaged the AHF on the desired hover altitude, the VRI and DVR rate field indicators are no longer presented on the display (i.e., they are turned off completely). They will remain off until either the AHF is disengaged or there is a change in desired hover altitude, at which time they will start flashing again.

As previously mentioned, a tradeoff exists between the presentation of the "big picture" and display magnification with respect to tracking error (Figure 6). An optimum display would somehow present the pilot with the "big picture" while still preserving the necessary sensitivity to allow accurate tracking. One strategy to cope with this tradeoff has been to provide the pilot with a number of selectable display modes, some of which involve altering the screen scale. However, this approach has several drawbacks.

Providing the pilot with selectable screen scales also provides the pilot with increased workload (i.e., "What screen scale shall I select?"). It also requires the pilot either to switch back and forth between various scales or select some middle-of-the-road scale that provides a reasonable sense of the "big picture" while allowing acceptable tracking with some compromises in operational capability. Furthermore, selectable display modes involve more switches, and this takes up more and more space in an already overly crowded cockpit (Dasaro and Elliott, 1981).

One alternative to the typical approach might be to provide the "big picture" and also provide a sensitive "vernier" index to allow precise tracking (Roscoe, 1968). A desired course line, next hover point, and distant hover point were added to provide the pilot with the "big picture" (Figure 11). The screen scale for the big picture symbology is equivalent to a 5 nmi radius. The positioning logic for the target cross has been changed to provide a vernier (magnified) instantaneous desired position indicator, and the unmagnified target position is no longer shown. The vernier scale for the target cross represents a radius of 250 feet (this scale can change as a function of mission requirements).

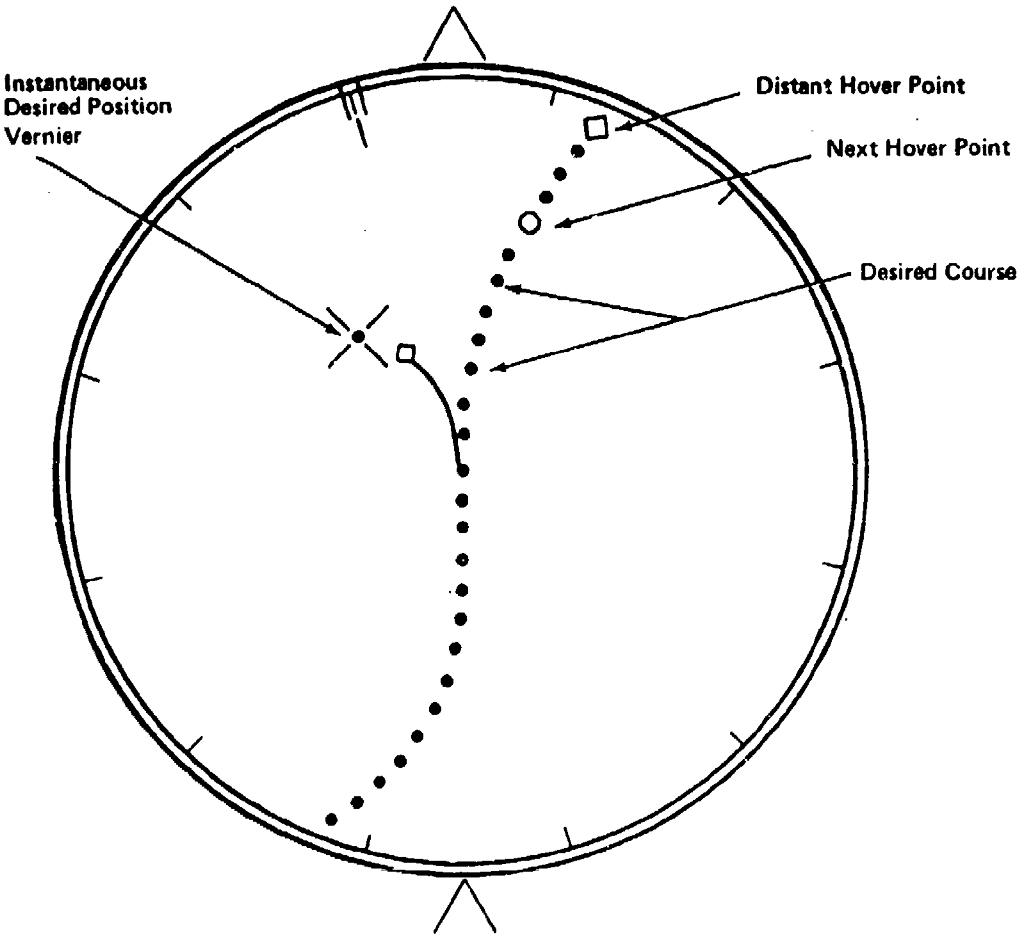


Figure 11. The big picture and the precise tracking symbols in the HOVERING display.

Three augmentations of the control system's characteristics were concluded as desirable during pretesting and subsequently incorporated. These included: 1) translational rate-hold function (TRF) 2) vertical rate-hold function (VRF), and 3) advanced control system laws to increase tracking accuracy and decrease workload. Buttons were provided on both the VSC and the side-arm translational controller to engage and disengage the rate-hold functions. The control system logic maintains the aircraft's present rate at the time a rate-hold function is engaged. To indicate that translational rate-hold has been engaged, an "H" replaces the small diamond symbol on the end of the flight-path predictor (Figure 12). Similarly, engagement of vertical rate-hold is indicated by an "H" superposed on the present altitude indicator.

The need for a vertical gain reduction (VGR) logic was associated with the high degree of variability in the display gain with respect to control inputs across different altitude scales. As a pilot ascends from the ground, the initial altitude scale limits are set at 60 feet. When the pilot ascends through the 60-foot mark (i.e., present altitude indicator dilates past 60 feet), the altitude scale limits become 250 feet (Figure 13). Once again, when the pilot ascends through the 250-foot mark, the altitude scale limits become 1000 feet, then 4000 feet, and so on (vise versa for descents). Each time a screen scale factor increases ("smaller picture") the display gain increases.

This caused an effective change in control/display ratio, even though control gain with respect to aircraft accelerations remained constant. The abrubt increases in display gain as the aircraft descended caused serious control instability by the pilot. Each time display gain changed, the pilot had to adjust to the change (i.e., essentially change his own gain) to make the appropriate control inputs. In effect a pilot must learn to transfer instantaneously from one control mode to another over a number of gain levels, which amounts to design-induced increases in workload and pilot error. To compensate for changing control/display sensitivity ratios, the VGR logic was programmed to change control gain by a suitable factor each time the screen scale changes.

Initially, it was intended to use some type of rate-field motion along the flight-path predictor as a translational rate indication. However, pretesting showed this feature to be ineffective and unnecessary, and it was eliminated in favor of sole dependence on the VDI for precise station keeping. The HOVERING display in its present developmental configuration is shown in Figure 14.

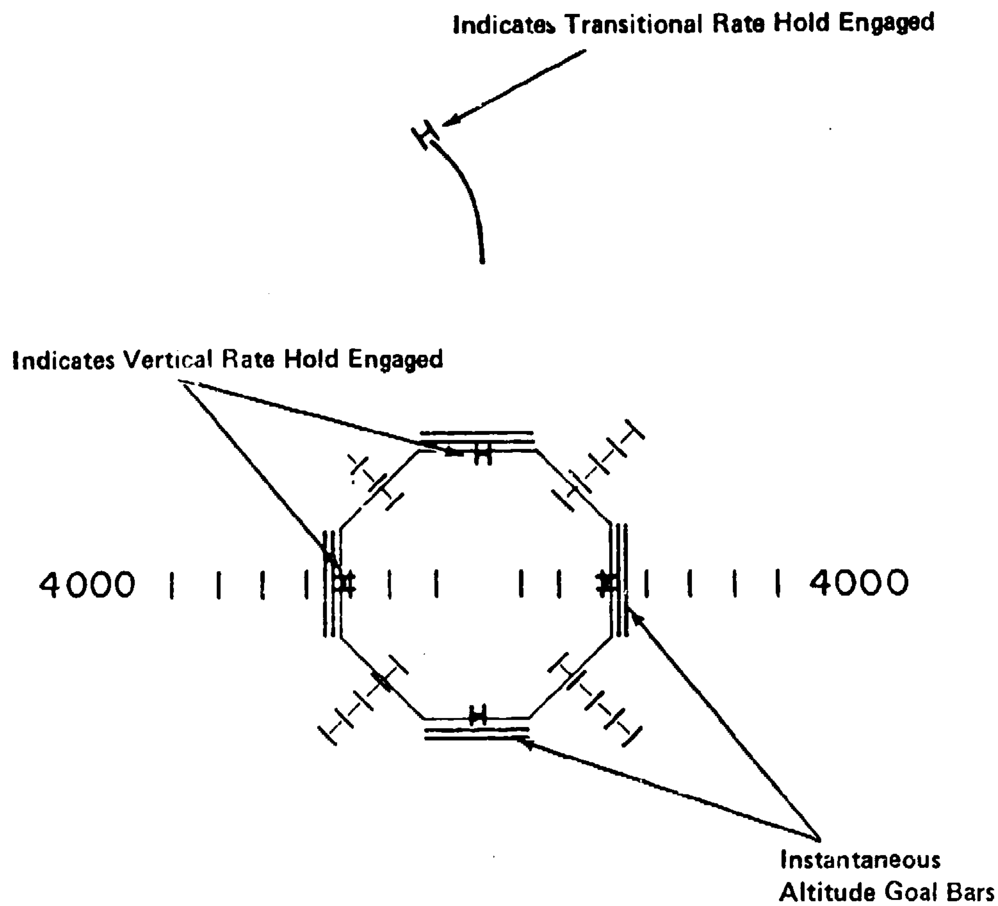


Figure 12. Symbology to indicate that the vertical and/or translational rate-hold functions are engaged; also instantaneous altitude goals bars.

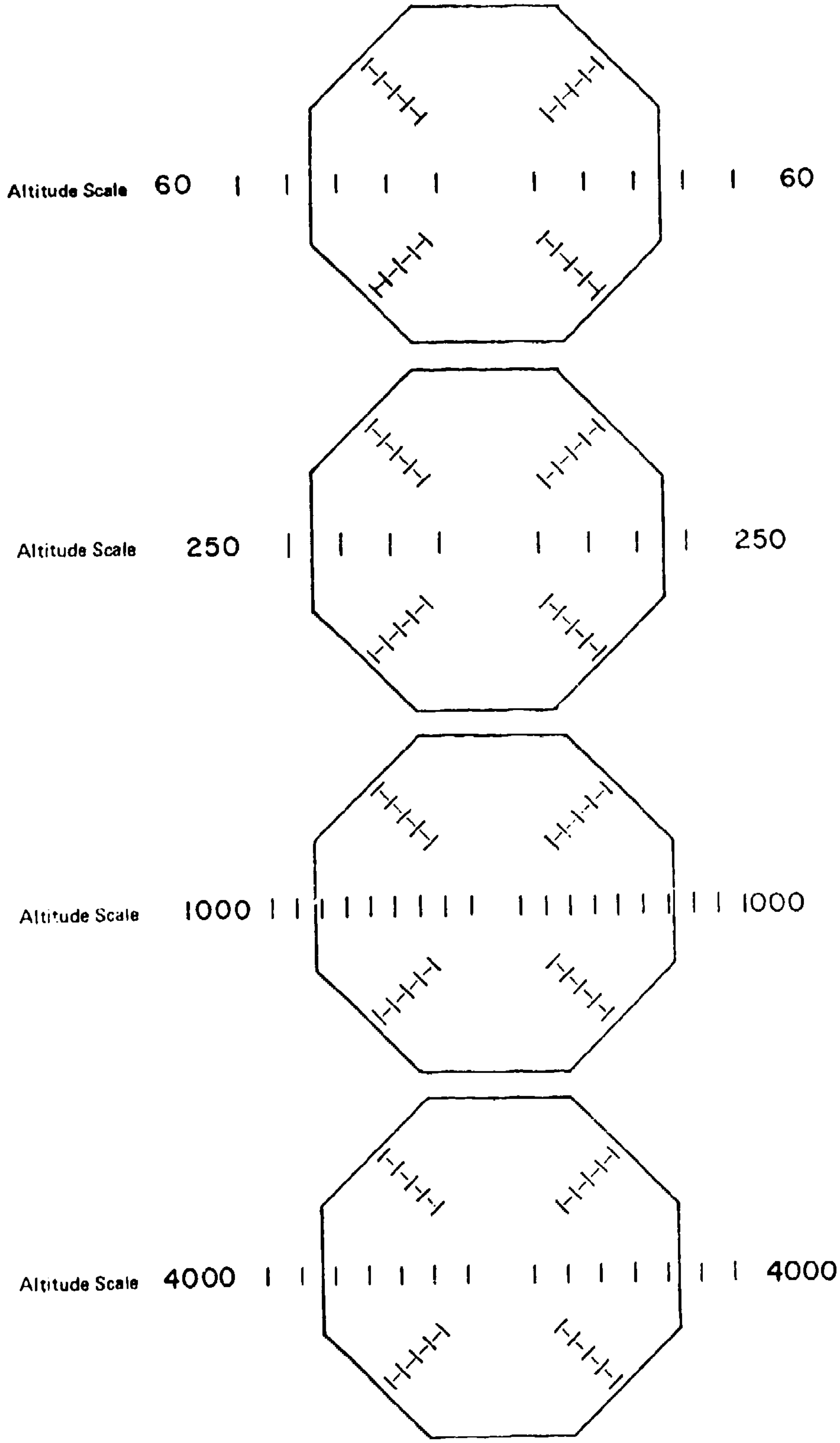


Figure 13. Example of altitude scale changes in the HOVERING display.

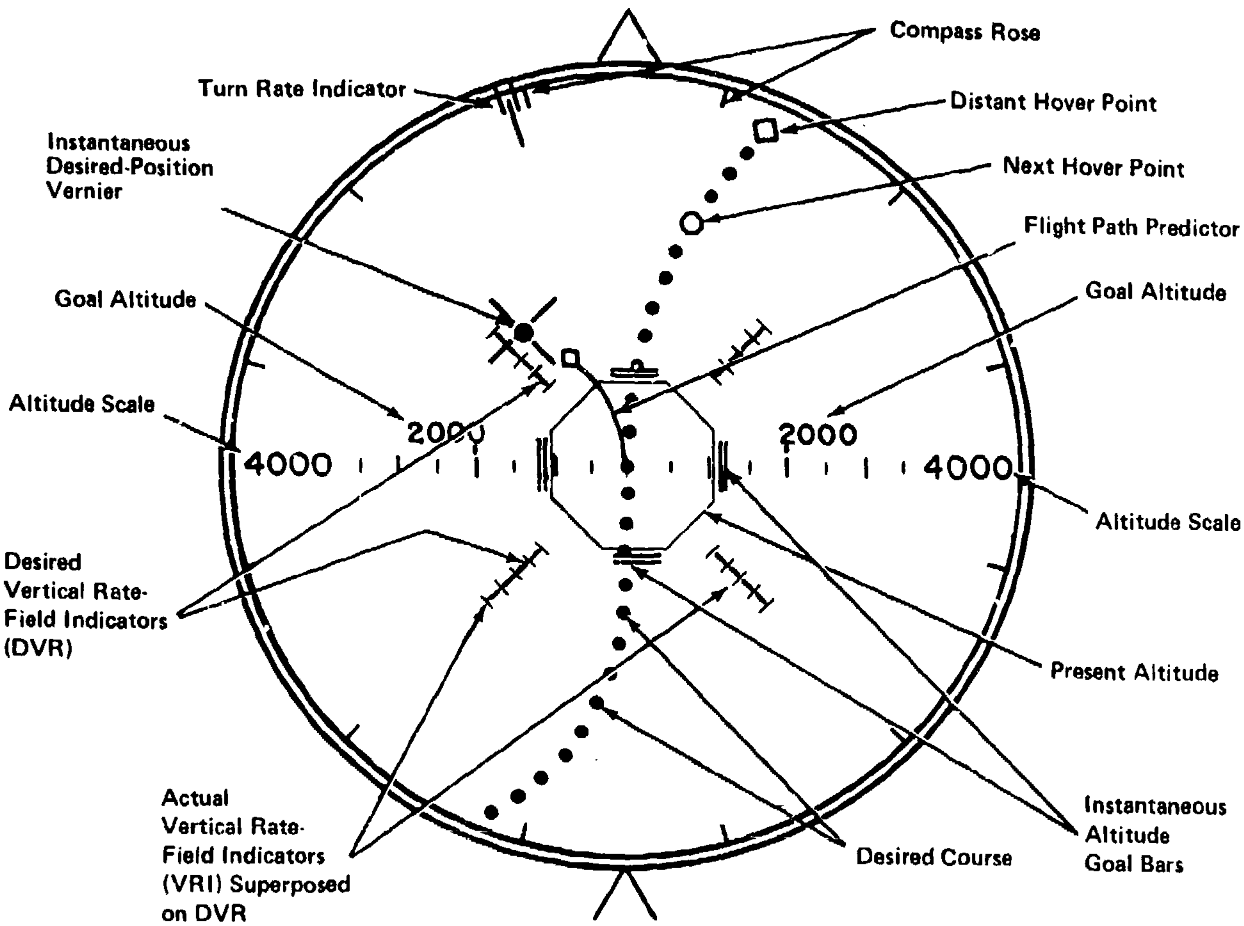


Figure 14. Present configuration of the HOVERING display.

PROBLEM

The general problem is the experimental optimization of the HOVERING display and control system. However, there are many potentially important variables that must be investigated, and therefore screening experiments are required to identify those design variables that have important effects on performance for inclusion in subsequent optimization experiments. Once the system has been optimized, it will be evaluated for operational potential. Following from the results of the evaluation, suggestions will be made to assist in the operational implementation of a HOVERING type display. Although this is basically an applied research effort, there is the potential for generalizable display principles to emerge.

The problem can be divided into three parts to facilitate its description: first, an analysis of the design variables involved; second, the experimental strategy; and third, the experimental tactics to implement the strategy.

ANALYSIS OF VARIABLES

Display Variables

The pretesting phase of the HOVERING display and control system's development indicated that the following display variables should be tested:

1. vehicle- versus target-referenced tracking
2. flight-path predictor computation
3. flight-path prediction time
4. flight-path prediction order
5. VDI magnification factor

Compensatory tracking tasks can be presented on a continuum between two extremes: vehicle-referenced and target-referenced. Vehicle-referenced compensatory (VRC) displays represent the vehicle's position as a fixed point, and only the target symbol moves as the result of either its own motion or a control input by the pilot of the vehicle. The pilot's task with this type of compensatory presentation is to bring the target to the vehicle. Target-referenced compensatory (TRC) displays represent the target (e.g., desired hover station or other aircraft) as a fixed point, and only the vehicle symbol moves. These two display modes are not mutually exclusive; the total position error can be divided into two parts and applied to the positions of the two display symbols in any ratio (Roscoe, Corl, and Jensen, 1981).

Compensatory tracking mode was selected as an important variable for two reasons. First, Dukes' display was developed using a TRC presentation while the prototype HOVERING display required VRC tracking. Comparison of the two tracking modes was considered essential for future operational applications. Second, early pretesting indicated that 50% TRC and 50% VRC was near optimum. Experimental quantification of this effect was needed. Figure 15 represents the HOVERING display in the TRC tracking mode. The target is seen as a fixed cross in the center of the screen and the vehicle (with flight-path predictor) as a moving "+" symbol.

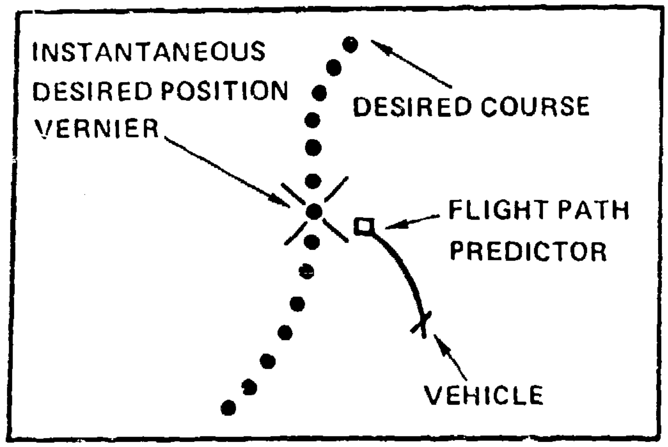


Figure 15. Example of the HOVERING display in the target-referenced tracking mode.

A conventional predictor is one that provides an indication of where a vehicle will be at some time in the future (Kelley, 1968; Poulton, 1974). Pretesting revealed that this sort of predictor was only marginally beneficial when tracking a moving target, but highly beneficial when approaching a fixed target such as a hover point. When a position predictor is used in approaching a fixed target, it becomes equivalent to an indicator of target closure rate. Because target closure rate appeared to provide superior indications for tracking accuracy, a second type of predictor was implemented using both the vehicle's and the target's positions, rates, and accelerations in its computation (Table 1). Quantification of the difference in tracking

performance between the conventional and closure-rate predictors warranted their inclusion in the investigation.

Prediction time was also determined to be an important variable. When a pilot is very close to a desired position, a short prediction time was found to be preferable. However, the larger the error the more important it is to have a longer prediction time. Quantification of the optimum prediction time for various phases of flight would be an important design consideration when optimizing the HOVERING display.

TABLE 1

COMPARISON OF TWO TYPES OF PREDICTOR COMPUTATIONS

Future Flight--Path Predictor:

$$\mathrm{Pos}\,(t + t_o) = \mathrm{Pos}\,(t_o) + (\mathrm{Vel}\,(t_o))\,t + (\mathrm{Accel}\,(t_o))\,t^2/2$$

$$+ \frac{\ldots\ldots\ldots + (\mathrm{Pos}^{(n)}\;(t_o))t^n}{N!}$$

Target--Closure Predictor:

$$\mathrm{Error} = \mathrm{Pos}_v - \mathrm{Pos}_t$$

$$\text{Therefore, Error}\,(t + t_o) = [\mathrm{Pos}_v\,(t_o) + (\mathrm{Vel}_v\,(t_o))\,t + \mathrm{Accel}_v\,(t_o))\,t^2/2] -$$

$$[\mathrm{Pos}_t\,(t_o) + (\mathrm{Vel}_t\,(t_o))\,t + (\mathrm{Accel}_t\,(t_o))\,t^2/2]$$

As with prediction time, order of prediction was determined to be an important variable for optimizing the HOVERING display. Prediction order refers to the number of integration terms that are included in the prediction computation. This variable was of interest for two main reasons: one, to determine the optimum prediction order for various orders of control and prediction times with respect to tracking performance, and two, to eliminate

unnecessary onboard computer processing time where possible. In other words, if higher-order predictors do not sufficiently improve tracking performance, then lower-order predictors should be implemented to save processing time.

VDI magnification factor was chosen as an experimental variable to assess the operational capabilities and limitations of the HOVERING display. VDI magnification factor was tested near both ends of the continuum (i.e., both high and low magnification) and at one intermediate point. Establishing the maximum trackable VDI magnification factor and its associated course error allows the evaluation of the HOVERING display in terms of minimum terrain avoidance limits allowable for various types of missions.

Control Variables

Pretesting of the HOVERING display and control system indicated that the following control variables should be tested:

1. control gain
2. control order
3. vertical gain reduction (VGR) logic

Control gain is a classic variable found in many experiments involving a variety of tracking tasks (Poulton, 1974). Control gain is often referred to in the context of control/display ratio (i.e., essentially effective display gain), but for the purpose of this experiment control gain and display gain (VDI magnification factor) were treated as independent variables. The effect of the interaction of these two variables on tracking performance is a reflection of variability in effective display gain.

High control gain allows faster target acquisition, but at the cost of less time on target. Low control gain causes slower target acquisition, but allows more time on target (Warner, Drennen, and Curtin, 1976). Control gain interacts with a number of different display variables (e.g., flight-path prediction time) and must be included in an experiment of this sort (Simon and Roscoe, 1981). Quantification of the effects of control gain across several mission phases is necessary in the optimization of the HOVERING display and control system, and it will also be helpful for future developmental considerations.

Control order has been demonstrated in several different contexts to affect tracking performance significantly (Poulton, 1974; Roscoe, 1980; Roscoe and Kraus, 1973; Simon and Roscoe, 1981; Warner, Drennen, and Curtin, 1976). In this initial experiment, control orders of 1.20, 1.31, and 1.46 were selected. Once again, the quantification of the effects of control order across a variety of display variables and mission phases is essential to the optimization and future development of the HOVERING display and control system.

In recent years, a number of researchers have investigated the implementation of onboard computers for advanced flight control systems in

aircraft (Neebe, Hissong, and Nelson, 1981; Porter and Bradshaw, 1982; Travassos, 1982). Porter and Bradshaw (1982) developed an advanced control system logic for the F-16 aircraft that allowed separation and stabilization of fuselage pitch pointing during constant vertical translational maneuvers. The HOVERING display and control system was developed with gain reduction logic that reduces the VSC stick gain by a factor of 0.545 each time the altitude display scale factor is increased by approximately 4 to 1. The reduction factor of approximately 0.5 was found to be quite acceptable during pretesting. However, values slightly above and below this were evaluated experimentally.

STRATEGY

As just discussed, numerous variables were evaluated and then selected for experimental testing. However, overall optimization of the system would become prohibitive in terms of experimental economy without first conducting a screening experiment to evaluate the relative criticality of the several display and control system variables. Those variables found to be highly critical in the initial screening experiment would then be included in a subsequent experiment designed to optimize the HOVERING display and control system. This report deals with the screening phase of the research.

Experimental Variables

All of the display and control variables previously discussed were included in this initial screening experiment with the exception of flight-path predictor type. This variable was eliminated for two reasons. First, a qualitative variable such as flight-path predictor type necessarily doubles the number of center points required to test for nonlinearity in the performance data. Second, Dukes (1970) had already made the distinction in flight-path predictor types and found, as we found informally, that target-closure predictors were more desirable than future flight-path predictors. Therefore, no attempt was made to replicate Dukes' findings, but the predictor in the experiment was based on target closure rate rather than future vehicle position.

The variables ultimately selected for consideration in this experiment included:

1. tracking mode (TM)
2. flight-path prediction time (PT)
3. flight-path prediction order (PO)
4. VDI magnification factor (MF)
5. control gain (CG)
6. control order (CO)
7. vertical gain reduction logic (GR)
8. initial position error (IP)

Initial position error was included as an experimental task variable because there was some indication during pretesting that second-order control systems provide better time on target, but first-order control systems allow faster target acquisition. An interaction between these two variables, with

respect to a given phase of flight, would be an indication that certain control systems serve certain phases of flight well but may not serve all phases of flight equally well.

Economical Designs

With the above variables, a design was required that could support a confident assessment of the relative criticality of display and control system variables without excessive data taking. A full factorial within-subject design would be experimentally prohibitive. With just two levels of each variable, each subject would be tested in 256 conditions. If each trial took only 30 seconds with a 15-second intertrial rest, and four trials were administered per condition to allow intraserial transfer effects to dissipate, more than 12 hours of flight testing would be required for each subject. Also, this estimate does not include center point observations and training time for each subject.

Simon (1973, 1976, 1977) pointed out that considerable economy could be attained if higher-order interactions are negligible. He reviewed 239 experiments reported in Human Factors and found that the proportion of variance accounted for by third-order interactions and higher was trivial. Also, as the number of factors increases, the proportion of variance accounted for by higher-order interactions approaches zero. If this can be assumed to hold generally true, then fractional factorial designs that confound main effects with higher-order interactions are available. If a main effect is confounded with a third- or fourth-order interaction and that interaction is negligible, then the confounding is nil, and the main effect is essentially unconfounded.

Asymmetrical Transfer

Poulton (1974) demonstrated that counterbalancing can be an ineffective (and even counterproductive) means for handling sequence effects in within-subject designs when asymmetrical transfer exists between experimental conditions. Asymmetrical transfer occurs when the transfer effect (facilitation or interference) from condition "A" to condition "B" is not the same as that from condition "B" to condition "A." If this is in fact the case, counterbalancing will not neutralize asymmetrical sequence effects and could bias the data systematically. When asymmetrical transfer is suspected, Poulton suggests that a between-subjects design be used. However, in large screening experiments, between-subjects designs become very costly.

In experiments involving many factors, within-subject designs are often essential for temporal, budgetary, or other practical considerations. If asymmetrical transfer exists, the data will be biased by the extent of the transfer asymmetry. The experimenter is now forced to choose among several alternatives: 1) reduce the number of factors involved in the experiment to a point at which a between-subjects design is feasible, 2) use a within-subject design and hope bias is negligible, 3) use a mixed design by assigning only those conditions most suspected of asymmetrical transfer as between-subjects factors, 4) choose not to conduct the experiment, 5) use some kind of fractional factorial within-subject design.

The first alternative is not desirable because limiting one's

experimental space may give less useful information than studying a large experimental space that contains a bias. The second choice is not reasonable because any conclusions about the data will be hedged by the bias assumption. Also, there is no reason to believe that there will be negligible asymmetry (especially considering the factors involved in the present experiment). The third alternative is fairly good, but its "goodness" depends on how many conditions are suspect of asymmetrical transfer. If the fourth choice were made, this report would terminate here. Hence, the choice was made to select alternative 5.

Alternative 5 involved a completely within-subject design (for purposes of economy) but with some qualifications. Informal investigation indicated that the asymmetrical transfer problem could be reduced by using highly skilled subjects. Each of three subjects was tested on 64 conditions. Extensive training was required before subjects could easily make the transitions among all 64 conditions, but the training was effective. In addition to using highly skilled subjects, extra "washout" or "buffer" trials were introduced between experimental conditions. Subjects were tested on four trials in each condition, the first three trials being used to allow carryover effects from one condition to the next to dissipate, and the fourth trial serving as the performance index for that condition.

TACTICS

Experimental Design

A resolution V fractional factorial design was selected for purposes of this initial screening experiment. In designs of this resolution, main effects are isolated (unconfounded) from themselves, second-, and third-order interactions. However, they are aliased with fourth-, fifth-, and higher-order interactions. The higher-order interactions are assumed to be negligible; thus, main effects are essentially unconfounded. Second-order interactions are unconfounded with main effects and themselves, but they are confounded with some third-order and higher-order interactions. Again, the confounding with higher-order effects is presumed negligible, but this assumption can be tested, and if it is not met, additional data can be collected to resolve the confounding.

A comprehensive explanation and discussion of the general notions, concepts, and mechanics involved in designs of this type has been presented by Simon (1973). By definition, all 2^{k-p} fractional factorials are themselves full 2^k factorials, where "2" is the number of levels of each factor, "k" is the number of factors in the experiment, and "p" represents the number of fractions taken from a complete 2^k factorial. Fractionating a full factorial is analogous to blocking, but in the case of fractional factorial designs some blocks are missing (i.e., left out for purposes of economy with essentially no loss of information, assuming confounding induced is nil).

A 2^{8-2} fractional factorial design was selected for this experiment based on its relative economy and high resolution (as these designs go, resolution V is considered very clean). This design consists of 4 blocks of 16 conditions or 64 observations per subject (Table 2). The letters in the table represent those conditions left from the original factorial after it was fractionated. The letters range from a-h, representing the eight factors, but without all of the original (2^8 or 256) factorial combinations. The letters defining each experimental condition represent the "+" level for the experimental factor associated with each particular letter. For example, condition 16 in block 1 is "ach," thus, in that condition, variables a, c, and h are set at their "+" values and all other variables at their "-" levels (note, the first condition, (1), has no letters, and therefore all eight variables are set at their "-" values).

The defining contrast (identity) for this particular design is: I = abceg = abdfh = cdefgh. Defining contrasts are selected when the original design is fractionated and are essential for determining where the confounding exists in the experiment (the mechanics of using defining contrasts will be discussed later). Whenever an experimenter has reason to suspect that a few of the higher-order interactions are truly strong effects, then strategic assigning of experimental factors can provide some safeguard against contaminating lower-order effects with significant higher-order effects. The technique for assigning experimental factors in designs of this sort is conceptually simple but lengthy in description and is not within the scope of this report. The

following section lists the experimental variables, their levels, and their association with the design shown in Table 2.

Variable Levels

Each experimental variable was assigned to one of the eight letters (a,b,c,...h) that represent conditions in the fractional factorial design shown in Table 2. (Remember that letters contained in each condition represent the "+" level of those particular experimental variables; all other

TABLE 2

THE 2^{8-2} FRACTIONAL FACTORIAL DESIGN USED IN THIS EXPERIMENT (from Astin, 1957)

	BLOCK 1	BLOCK 2	BLOCK 3	BLOCK 4
1.	(1)	bdefh	acdefgh	abcg
2.	abcfgh	acdeg	bde	fh
3.	bcdeg	cfgh	abfh	ade
4.	adefh	ad	cg	bcdefgn
5.	efgh	bdg	acd	adcefh
6.	abce	acdfh	bdfgh	ag
7.	bcdfh	ce	abeg	adfgh
8.	adg	abdfgh	cefh	bcd
9.	cdgh	bcefg	aef	abdh
10.	abdf	aeh	bcegh	cdfg
11.	beh	df	abcdfg	acegh
12.	acefg	abcdgh	gh	bef
13.	cdef	bch	agh	abdefg
14.	abdegh	afg	bcf	cdeh
15.	bfg	degh	abcdeh	aef
16.	ach	abcdef	defg	bgh

variables are then set at their "-" value.) The experimental variable levels and their association with the experimental design are shown in Table 3. The "0," or centerpoint, defines a central condition that is used for an

economical test for nonlinearity in the data. The incorporation of central conditions into an existing design will be discussed next in more detail.

TABLE 3

EXPERIMENTAL VARIABLE LEVELS AND THEIR ASSOCIATION WITH THE DESIGN IN TABLE 2

Label	Experimental Variable	Variable Levels (-)	Variable Levels (0)	Variable Levels (+)
a	Tracking mode (TM)	75%VRC	67%VRC	56%VRC
b	Prediction time (PT)	0.34s	0.50s	0.67s
c	Prediction Order (PO)	1st	-----	2nd
d	Magnification (MF)	66	100	134
e	Control gain (CG):			
	longitudinal (1st order)	-6300	-8000	-9700
	longitudinal (2nd order)	-124	-162	-201
	lateral (1st order)	13950	16500	19050
	lateral (2nd order)	665	750	835
	azimuth (1st order)	0.57	0.90	1.10
	azimuth (2nd order)	0.32	0.44	0.56
	vertical (1st order)	-1575	-2000	-2425
	vertical (2nd order)	-72	-87	-104
f	Control order (CO)	1.21	1.31	1.46
g	Gain reduction logic (GR)	41%	52%	60%
h	Initial position error (IP):			
	alongcourse error	43 feet	60 feet	77 feet
	crosscourse error	22 feet	30 feet	39 feet
	altitude error	116 feet	150 feet	184 feet

Center Points

In experiments involving only two levels of "k" factors, linearity must be assumed to exist between the two levels of each experimental variable. If

the data in fact are nonlinear, then any regression equation that best describes the actual performance scores obtained will only generalize to the specific values chosen for experimentation. Thus, the equation will be virtually useless, and likely misleading, in an applied context. There are two procedures that can be used to deal with problems of nonlinearity in two-level factorial experiments. First, the levels chosen for each experimental variable must be scaled linearly. And second, center points can be incorporated into the existing design to allow a test of the linearity assumption (Simon, 1977).

Variable scaling is analogous to transforming distributions of data. However, the significant difference is that variable scaling is done before the fact and transforming data occurs after the data have been collected. During the pretesting phase of experimentation, the response surface of each individual variable must be determined whenever economically feasible. If the response surface tends to be linear, then that particular variable should be scaled linearly. If the response surface indicates curvature, then that particular variable should be scaled with an appropriate transformation, one that linearizes the function that best describes that variable's response surface. For example, in this experiment, the VDI magnification factor (MF) was scaled linearly, but control order (CO) was scaled logarithmically (Table 3).

The use of linearized scaling, when assigning values to levels of experimental variables, can increase the generalizibility of predictive equations substantially. If the scales chosen are not quite linear, the extent of the nonlinearity must be assessed. Simon (1977) described a method of augmenting 2^{k-p} fractional factorial designs by collecting data at a central condition. For continuous variables this presents no problem; the central condition is defined by that point falling "midway" between the two experimental levels (exactly where that is depends on the scale chosen for that variable). However, qualitative variables have no definable central point. To handle this problem, the "+" and "-" value of each qualitative variable must be tested with all continuous variables set at their center points, a costly process.

Fortunately, this experiment has only one qualitative variable. Thus, there are two central conditions in which data must be collected to test for linearity. Flight-path prediction order must be combined at both its "+" and "-" levels with all other variables set at their center points (Table 3). The data obtained for the two central conditions are averaged and then compared with the overall mean of each dependent variable as a gross test of linearity. If there appears to be a substantial departure from linearity, then additional data may be collected.

Subjects

Three pilots were used as subjects for this initial screening experiment. The pilots were required to have at least a private pilot's rating and no motor control impairment. Selection was based on willingness and availibility to serve as test pilots for several long training and testing sessions. As incentive, each pilot received a trophy award commensurate with his relative performance.

Flight Task

The flight task chosen for this experiment consisted of a 30-second climbing turn to the right, essentially a standard instrument departure (SID). Although this initial investigation was limited to a single flight task, other phases of flight must be investigated at a later time. A description of the simulated VTOL model used in this investigation is provided in Appendix A.

Performance Measures

In tracking tasks, such as that involved in this experiment, distributions of RMS errors tend to be positively skewed (in accordance with the distribution of the Chi-square). To approximate a normal distribution of tracking errors, log RMS error was chosen as the appropriate measure of alongcourse, crosscourse, and altitude tracking accuracy. The log RMS error scores were based on samples taken once per second. Measurements were not made during the first 5 seconds to guard against subject inattentiveness at the outset of a trial. Post hoc examination of the distributions of log RMS scores supported the appropriateness of the transformation.

Procedure

Each 30-second SID was followed by a 15-second intertrial interval. Each pilot completed eight 51-minute training sessions, two in each of four experimental blocks (Table 2). Center point data were collected before and after each experimental block. Therefore, each 51-minute training session consisted of single trials in each of two central conditions (i.e., center point for all continuous variables and both levels of the qualitative variable, prediction order), followed by four trials in each of 16 experimental conditions, and a final set of trials in the two central conditions. Two blocks were completed in a given day by each pilot with an hour's rest period between blocks.

Once training was completed, the pilots were tested over the four blocks of experimental conditions in two consecutive days with an hour's rest between blocks. All three pilots were tested in the same serial sequence (i.e., blocks one and two (day one) and blocks three and four (day two); recall Table 2). Again, note that data from the first 5 seconds of each trial were not included in computing trial scores to minimize perturbations in the data due to lack of readiness at the outset of a trial.

Intraserial Condition Sequence

There are several methods available to minimize bias in data due to intraserial transfer (carryover) effects. Using highly trained subjects can be an effective guard against trend due to learning. However, counterbalancing is the most effective means available to minimize trend effects such as fatigue, etc. Although no explicit attempt was made to counterbalance conditions in this experiment, there is a great deal of counterbalancing within the existing design. Simon (1977) found that main effects in this design are orthogonal to intraserial trends, and also that second-order effects are essentially unconfounded.

As mentioned, counterbalancing is effective only if transfer effects

between conditions are symmetrical. Pretesting indicated that using highly trained subjects and including buffer trials in each condition allowed any asymmetrical condition-to-condition carryover effects to dissipate.

<u>Analysis of Effects</u>

One of the most beautiful features of economical multifactor designs is the relative simplicity of computations required for analysis. Yates (1937) described a tabular method for determining the effects (i.e., mean differences) of experimental variables in designs involving only two levels of k factors (Simon, 1977; 1981). The computations involve only addition and subtraction, with the exception of a single division necessary to complete the analysis. The following description of Yates' method is based on a report by Simon (1977).

The performance data must be listed in Yates' standard order, namely, (1), a, b, ab, c, ac, bc, abc, d, etc. Once the performance data are placed in standard order, additional columns are added next to the performance data (the number of columns being equal to the exponent "k-p", with "k" the number of factors in the experiment and "p" the number of fractions thereof). Next, the sum of the first and second scores are entered at the top of the first column, followed by the sums of each succeeding pair of scores until all $2^k/2$ pairs have been summed and entered (Table 4). To fill in the remainder of the first column, the first score is subtracted from the second score (beginning with the first pair in the performance data column) and is entered in the next open row in the first column. The subtraction procedure is continued with each succeeding pair until the first column is complete.

TABLE 4

EXAMPLE OF YATES' ALGORITHM IN A 2^3 FACTORIAL EXPERIMENT

Standard Order	Experimental Condition	Performance Data	Columns 1	2	3	Mean & 2^{k-p} Effects
1)	(1)	5	6	12	33	4.125
2)	a	1	6	21	1	0.25
3)	b	2	16	-2	-11	-2.75
4)	ab	4	5	3	5	1.25
5)	c	7	-4	0	9	2.25
6)	ac	9	2	-11	5	1.25
7)	bc	2	2	6	-11	-2.75
8)	abc	3	1	-1	-7	1.75
Total		33.0				

The entire procedure is repeated with each new column generated from its predecessor until all of the columns have been completed. As a simple accuracy check, the first entry in the final column should equal the sum of the values in the performance data column. It is followed by what are called the "effect totals." To determine the grand mean plus individual effects (or mean differences), the first position in the last column is divided by 2^k, and the remaining effect totals are divided by $2^k/2$ (Table 4).

Although this method of analysis is relatively simple, as the number of factors increases, the probability of arithmetic error increases tremendously. Therefore, practical application of Yates' method requires the use of a computer program. Following from Yates' algorithm, a general UCSD Pascal program was developed capable of analyzing two-level factorial and fractional factorial experiments up to 256 conditions (this capability could easily be expanded). To compute the effects in this experiment, each pilot's fourth trial in a given experimental condition provided his individual performance score for that condition. The mean of the three pilots' scores in each condition was computed, and these values were then entered in the "Performance Data" column in the standard order (recall Table 4) and analyzed using Yates' algorithm.

RESULTS

The mean and 63 effects (in log RMS error) for each performance measure are listed in Yates' standard order in Table 5.

Determining Real Effects

As an alternative to the typical tests of significance, a method of determining real effects from those no greater than chance was first described by Daniel (1959) and later refined by Zahn (1975). This method involves plotting normalized effects against absolute rank order on probability paper (i.e., normal-order plots). The probability values that correspond to each rank position on the normal plot must be estimated based on the number of effects to be tested. If all of the experimental effects are distributed purely by chance (i.e., no real effects), then those effects should fall along a straight line when normalized and plotted against absolute rank order on normal probability paper.

Therefore, if the null hypothesis is tenable for normally distributed data, effects will plot along a straight line (Simon, 1977). To the extent that effects are greater than any expected purely by chance, departure from a straight line will occur. Whether the departure from chance is "significant" or not is determined by the addition of guardrails to the probability plot. Guardrail values must be determined by estimating expected values and variances for each rank. If we assume that the experimental effects are normally distributed with mean = 0 and variance = 1, then: for samples drawn from this population of size n, the expected value and variance of each rank can be estimated (Westra, personal communication).

Simon (1977) provides tables of probability values required to plot 15, 31, and 63 ordered effects. Based on his tables, a normal probability plot was constructed for 63 effects. Plotting the data requires that the effects be normalized (converted to z-scores) and rank ordered from the smallest to the largest effect. The normalized and ordered effects for each dependent variable are shown in Table 6. Note that each effect in the table is followed by a number (1,2,3,...63). This number represents each effect's original position in Yates' standard order before the effects were normalized and ordered. This is important in identifying which ranks are associated with which experimental sources of variance (i.e., main effects, second-order interactions, etc.).

Before plotting the effects, the decision was made to use 0.40 guardrails. This critical value is based on the probability error rate for the family of contrasts involved in the experiment. Therefore, the actual probability error rate for each individual comparision is:

$$1 - (1 - pc)^k = \text{per}$$

TABLE 5

MEAN AND 63 EFFECTS IN YATES' STANDARD ORDER FOR EACH PERFORMANCE MEASURE

	Crosscourse Error	Alongcourse Error	Altitude Error
	1.14761	1.25446	1.56729
1.	1.02233E-2	2.10719E-2	3.14137E-2
2.	2.47959E-2	2.38157E-2	3.10700E-3
3.	5.88256E-2	4.32390E-2	-1.48608E-2
4.	-6.47140E-3	8.26789E-3	4.07799E-2
5.	2.45241E-2	4.15461E-3	1.80731E-2
6.	-3.98015E-2	-1.89062E-2	1.41342E-2
7.	-3.51456E-2	-1.97031E-3	8.33792E-3
8.	-2.36053E-2	-4.69748E-2	4.13744E-2
9.	7.77055E-3	-4.08275E-3	3.25898E-2
10.	-3.39041E-2	-2.31812E-2	-7.00149E-2
11.	-5.57141E-2	-1.19129E-2	3.01829E-2
12.	3.12526E-2	-3.41289E-2	-4.88980E-3
13.	2.41537E-2	-6.40443E-2	3.36316E-2
14.	6.14692E-2	3.86547E-2	5.14609E-2
15.	3.92745E-2	2.17337E-2	4.38306E-2
16.	-6.68347E-4	-1.44271E-2	2.35236E-2
17.	-1.15224E-3	1.26655E-2	3.49320E-2
18.	-5.47184E-2	-7.82445E-2	-8.25293E-2
19.	-1.21032E-1	-6.80068E-2	-3.96527E-2
20.	5.32165E-2	2.35817E-2	-1.95542E-2
21.	5.64719E-3	-1.46363E-2	-4.70355E-4
22.	-3.05714E-2	3.30210E-2	5.16020E-2
23.	-6.14269E-2	6.34662E-3	2.33456E-4
24.	2.65852E-3	-2.42513E-2	-1.65559E-2
25.	-7.34594E-3	-1.09550E-4	-2.94248E-2
26.	-7.26235E-3	-5.19630E-3	-3.45319E-3
27.	-3.92967E-2	-2.96070E-2	4.10321E-2
28.	1.13966E-2	-7.14997E-2	-1.78970E-2
29.	-4.91768E-2	4.08459E-2	-2.35358E-2
30.	-4.90920E-3	-4.48702E-2	-4.21255E-3
31.	3.31087E-3	2.10282E-2	-1.18012E-2
32.	-3.55804E-2	-5.55916E-2	3.30567E-4
33.	5.11205E-2	8.32412E-2	1.54334E-2
34.	-2.47151E-2	-3.01802E-2	-4.20116E-2
35.	-5.63559E-2	1.74639E-2	3.71086E-2
36.	1.06722E-2	-5.30456E-3	3.29308E-2
37.	2.96193E-2	3.71324E-2	2.68866E-2
38.	-1.62108E-2	8.28403E-3	2.40233E-3
39.	-9.86533E-3	-1.12262E-2	1.66545E-2
40.	1.40319E-2	-2.92420E-3	-4.06891E-4
41.	-2.44926E-2	-5.99752E-3	1.31740E-2
42.	1.04981E-2	-3.60875E-2	-2.38177E-2
43.	-5.00438E-2	-1.28783E-2	9.88144E-3
44.	-1.06947E-2	-1.39187E-2	4.77016E-2
45.	1.65231E-2	-4.61707E-2	-1.18250E-2
46.	-6.51057E-3	1.86096E-2	1.02064E-1
47.	7.36165E-2	5.07055E-2	1.21249E-1
48.	-3.44794E-2	-2.26043E-2	-7.46021E-2
49.	2.02441E-2	-3.00418E-2	1.78178E-2
50.	-1.77162E-2	-5.20227E-2	-1.56669E-2
51.	-4.44437E-2	-5.86513E-2	-1.98843E-2
52.	2.38615E-3	1.69955E-2	1.38529E-2
53.	6.06236E-2	1.53971E-1	1.13666E-1
54.	3.23180E-4	8.72885E-2	-4.16500E-2
55.	-3.71213E-3	-3.44707E-2	1.31588E-2
56.	7.16826E-3	4.60187E-2	-3.01419E-2
57.	3.79910E-2	-1.17501E-3	-6.15616E-2
58.	1.96974E-1	1.87064E-1	5.61539E-3
59.	-4.08858E-2	-2.44835E-2	-1.18425E-2
60.	-4.60279E-3	-1.12595E-3	3.14318E-3
61.	1.71499E-2	-1.79514E-2	8.51916E-2
62.	-2.58579E-2	5.64165E-3	6.97066E-2
63.	5.54191E-4	-2.46178E-3	-7.40001E-3

TABLE 6

NORMALIZED AND ORDERED EFFECTS WITH ORIGINAL YATES' POSITION SHOWN

Crosscourse Error		Alongcourse Error		Altitude Error	
4.54133	58	4.00893	58	2.76451	47
1.71556	47	3.30034	53	2.57781	53
1.43730	14	1.87256	54	2.29199	46
1.41793	53	1.78590	33	1.87635	61
1.37674	3	1.08925	47	1.49488	62
1.24826	20	9.88901E-1	56	1.04888	22
1.20024	33	9.29382E-1	3	1.04541	14
9.28885E-1	15	8.78139E-1	29	9.52798E-1	44
8.99483E-1	57	8.31225E-1	14	8.57438E-1	15
7.45126E-1	12	7.98630E-1	37	7.96928E-1	8
7.07710E-1	37	7.10598E-1	22	7.88497E-1	27
5.97220E-1	2	5.13496E-1	2	7.82285E-1	4
5.90994E-1	5	5.08485E-1	20	6.91849E-1	35
5.82510E-1	13	4.68916E-1	15	6.38272E-1	17
4.92952E-1	49	4.54745E-1	1	6.06188E-1	13
4.22074E-1	61	4.53811E-1	31	5.88974E-1	36
4.07714E-1	45	4.02025E-1	46	5.80525E-1	9
3.50647E-1	40	3.77492E-1	35	5.51552E-1	1
2.90281E-1	28	3.67463E-1	52	5.21231E-1	11
2.73687E-1	36	2.74750E-1	17	4.40028E-1	37
2.69698E-1	42	1.80936E-1	38	3.57181E-1	16
2.63405E-1	1	1.80590E-1	4	2.22910E-1	5
2.07219E-1	9	1.39452E-1	23	2.16620E-1	49
1.93422E-1	56	1.24358E-1	62	1.87964E-1	39
1.58578E-1	21	9.25177E-2	5	1.57631E-1	33
1.05060E-1	31	1.21470E-3	25	1.25875E-1	6
9.01163E-2	24	-2.05481E-2	60	1.18957E-1	52
8.38772E-2	52	-2.15787E-2	57	1.02222E-1	41
4.19121E-2	63	-3.86275E-2	7	1.01845E-1	55
3.66203E-2	54	-4.91507E-2	63	2.11101E-2	43
1.39073E-2	16	-5.90519E-2	40	-1.69139E-2	7
2.82268E-3	17	-8.38584E-2	9	-8.39826E-2	58
-5.58173E-2	55	-1.07701E-1	26	-1.44885E-1	60
-7.62197E-2	60	-1.10019E-1	36	-1.45776E-1	2
-8.32158E-2	30	-1.24357E-1	41	-1.63135E-1	38
-1.19024E-1	4	-2.36813E-1	39	-2.14173E-1	32
-1.19921E-1	46	-2.51516E-1	11	-2.15565E-1	23
-1.37143E-1	26	-2.72187E-1	43	-2.32340E-1	40
-1.39057E-1	25	-2.94462E-1	44	-2.33903E-1	21
-1.96770E-1	39	-3.05348E-1	16	-3.07394E-1	26
-2.15768E-1	44	-3.09828E-1	21	-3.26091E-1	30
-3.42126E-1	38	-3.80811E-1	61	-3.42775E-1	12
-3.76611E-1	50	-4.01254E-1	6	-4.04613E-1	63
-5.11514E-1	8	-4.80438E-1	48	-5.13035E-1	31
-5.31839E-1	41	-4.92788E-1	10	-5.13621E-1	45
-5.63113E-1	62	-5.15703E-1	24	-5.14052E-1	59
-6.71086E-1	22	-5.20674E-1	59	-5.88407E-1	3
-7.47431E-1	10	-6.30377E-1	27	-6.08266E-1	50
-7.60609E-1	48	-6.39686E-1	49	-6.30190E-1	24
-7.66007E-1	34	-6.42650E-1	34	-6.63203E-1	28
-7.75869E-1	7	-7.27197E-1	12	-7.04029E-1	20
-7.85829E-1	32	-7.34516E-1	55	-7.12158E-1	51
-8.70958E-1	27	-7.69135E-1	42	-8.02114E-1	29
-8.82573E-1	6	-9.57188E-1	30	-8.09058E-1	42
-9.07342E-1	59	-9.85014E-1	45	-9.47186E-1	25
-9.88863E-1	51	-1.00225	8	-9.64853E-1	56
-1.09729	29	-1.11033	50	-1.19915	19
-1.11715	43	-1.18675	32	-1.24835	54
-1.22423	18	-1.25227	51	-1.25726	34
-1.24703	11	-1.36774	13	-1.73987	57
-1.26174	35	-1.45258	19	-1.94711	10
-1.37790	23	-1.52737	28	-2.06011	48
-2.74329	19	-1.67179	18	-2.25540	18

where, "per" is the probability error rate for the family, "pc" is the probability error rate for each individual comparison, and "k" is the number of factors in the experiment. Solving for pc with k = 8, and per = 0.40, the probability error rate for each individual comparison is approximately 0.06. However, this error rate holds only for the largest effect found significant. The error rate for each succeeding effect found significant will be slightly different; the differences are minor, and for purposes of this experiment the probability error rate for all individual contrasts will be considered to equal 0.06.

Plots of the 63 normalized effects for each dependent variable are shown in Figures 16-18. Most of the points fall along a straight line as would be expected by chance. Those effects that fall outside the critical limits represented by the 0.40 guardrails are considered significant. For crosscourse tracking (Figure 16), the significant factor effects are MF (magnification factor) and PT (flight-path prediction time). For alongcourse tracking (Figure 17) MF, CO (control order), CG (control gain), and TM (tracking mode) are all significant factors. For altitude tracking (Figure 18), GR (vertical gain reduction logic), CO, PT x IP, IP, TM x PO, TM x PO x MF, and 2 strings of three-factor interactions (3 FIs) are all outside the 0.40 guardrail and therefore are significant (GR x IP fell noticeably off the chance line but within the guardrails and thus is not considered significant).

The significant factor effects and interactions are summarized in Table 7, which also includes the percent of variance accounted for by each significant effect. Significant effects accounted for 45% of the crosscourse tracking variance, 54% for alongcourse tracking, and 60% for altitude tracking. The direction of an effect can be determined from the normal-order plot in conjunction with the position and direction of the effect in Yates' standard order. However, the procedure is somewhat involved and beyond the scope of this report. Appendix B provides an easily discerned graphical picture of each significant effect.

Regression Coefficients

After determining which effects are important, predictive regression models are readily formed. The coefficients for each factor can be obtained by dividing each factor's effect by two (Simon, 1977). Regression equations for crosscourse, alongcourse, and altitude tracking are summarized in Table 8.

Determining Confounding

In designs of this type, analysis is not complete without determining whether the significant effects are clean of confounding, and if not, the extent and consequence of that confounding. The defining contrast (identity) for the design used in this experiment is: I = abceg = abdfh = cdefgh. To determine where confounding exists in each significant effect, each defining

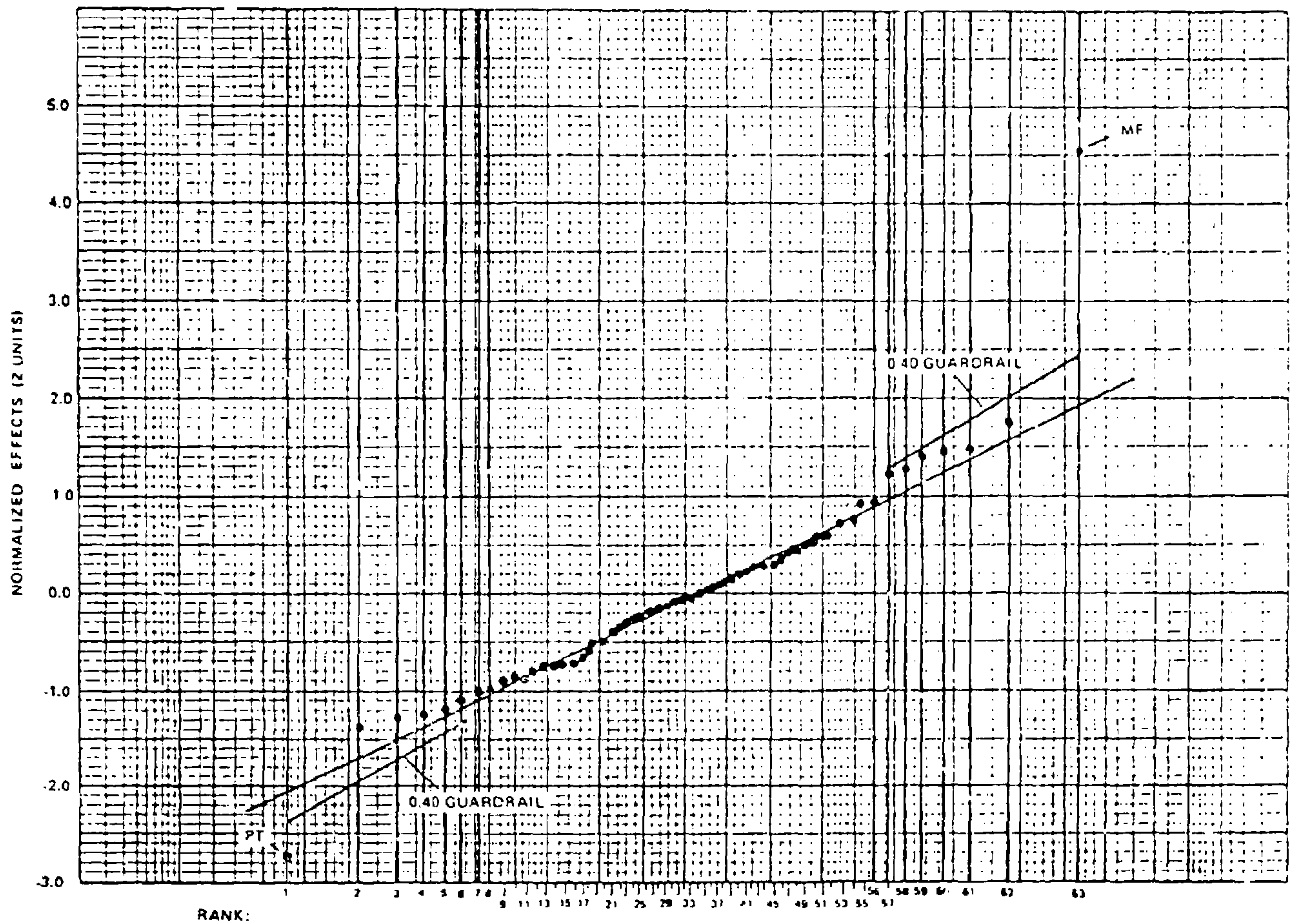


Figure 16. Normal-order plot for crosscourse tracking error.

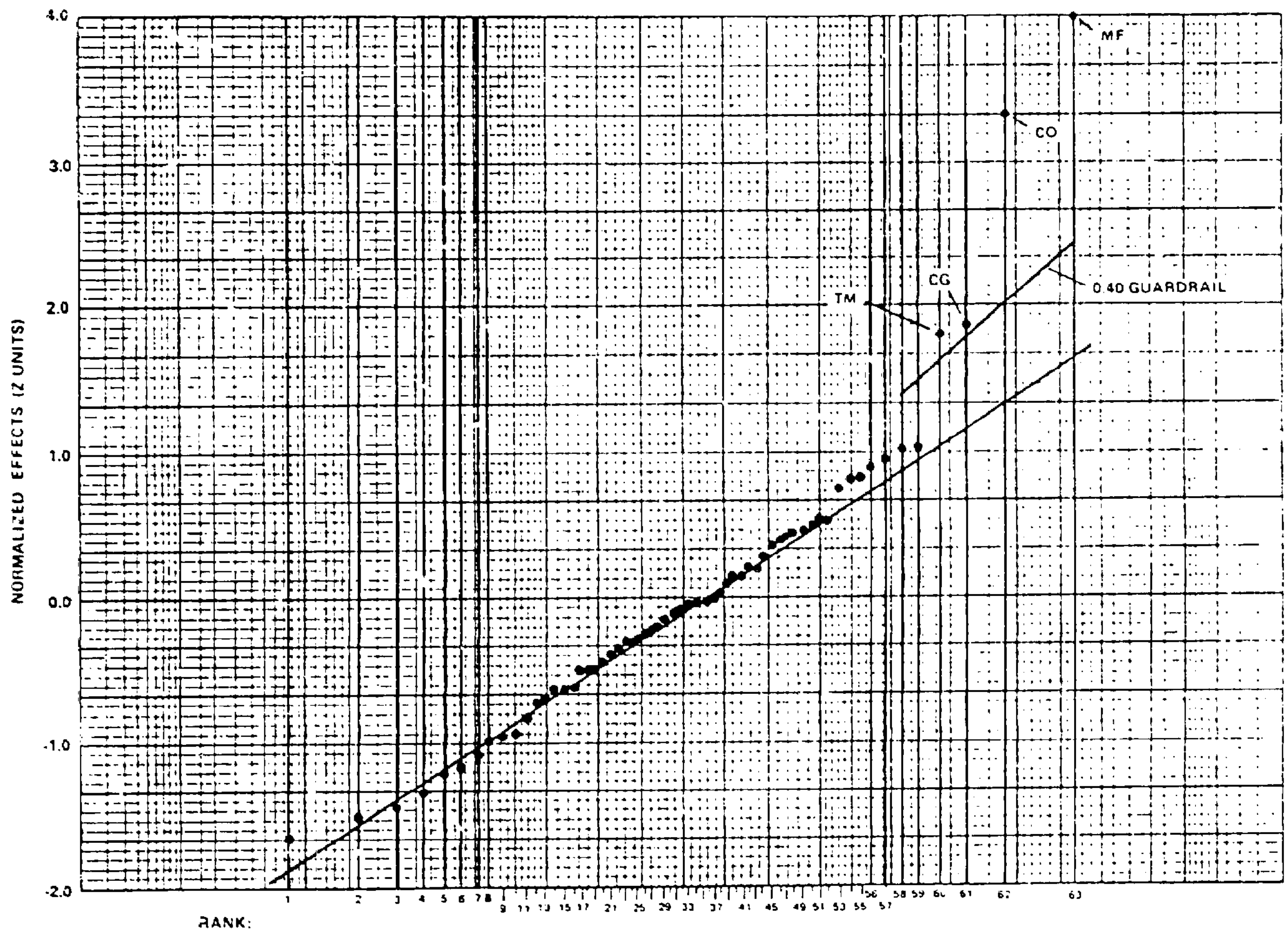


Figure 17. Normal-order plot for alongcourse tracking error.

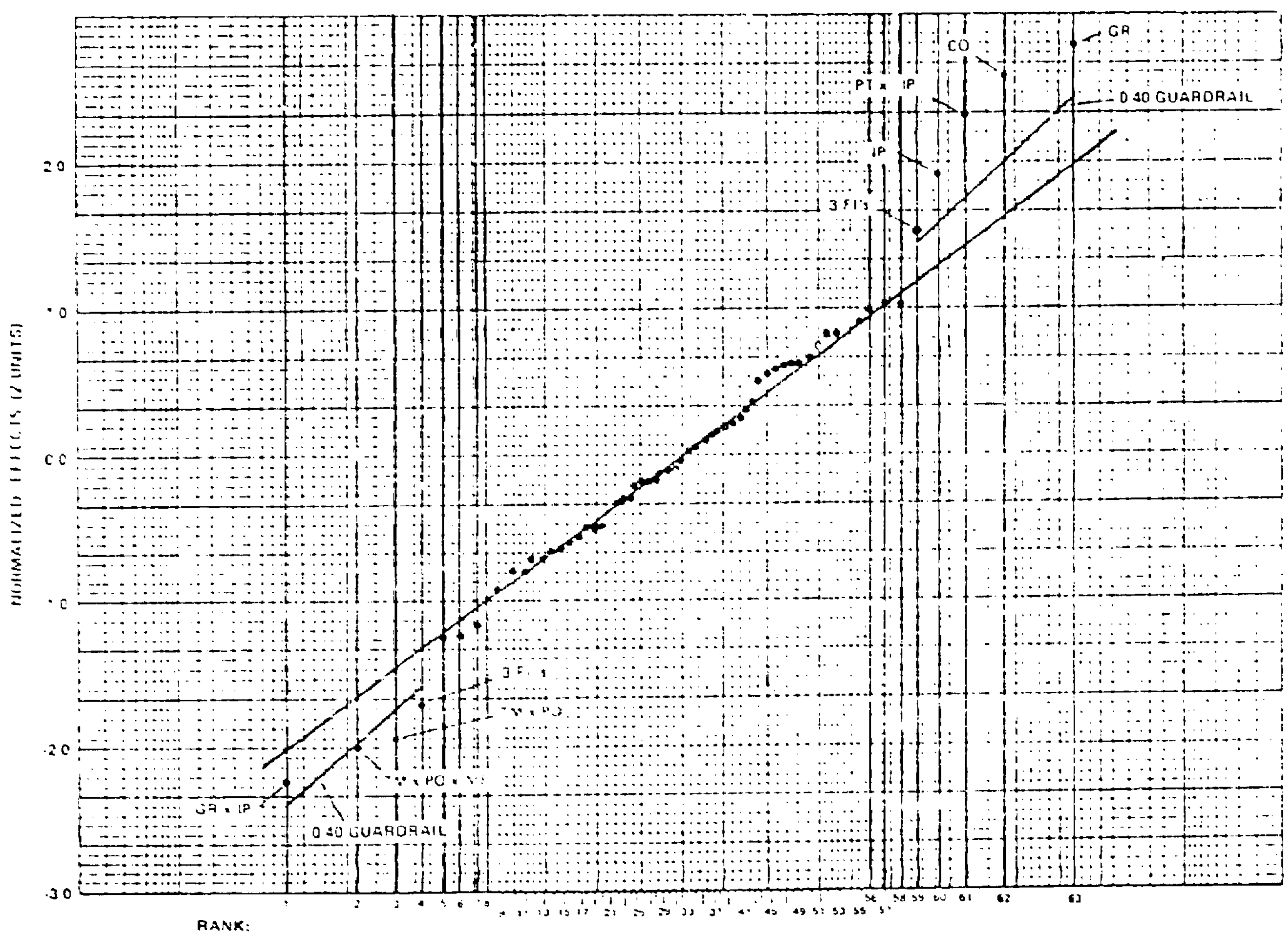


Figure 18. Normal-order plot for altitude tracking error.

TABLE 7

SUMMARY OF IMPORTANT EFFECTS ($p < 0.06$) FOR CROSSCOURSE, ALONGCOURSE, AND ALTITUDE TRACKING ERRORS

	Percent of Variance Accounted for (eta^2)		
Effect	Crosscourse Error	Alongcourse Error	Altitude Error
GR	----	----	13.7
MF	32.6	25.9	----
CO	----	17.5	12.0
PT	12.4	----	----
CG	----	5.6	----
TM	----	5.1	----
PT x IP	----	----	9.7
IP	----	----	6.7
TM x PO x MF	----	----	5.2
TM x PO	----	----	4.6
3FIs	----	----	4.5
3FIs	----	----	3.5
TOTAL	45.0	54.1	59.9

TABLE 8

REGRESSION EQUATIONS FOR CROSSCOURSE, ALONGCOURSE, AND ALTITUDE TRACKING

<u>Crosscourse</u> <u>Error:</u>

MEAN = 1.148 (log RMS error in feet; hence, RMSE = 15 feet)

REGR = 1.148 - 0.098(MF) - 0.061(PT)

<u>Alongcourse</u> <u>Error:</u>

MEAN = 1.254 (log RMS error in feet; hence, RMSE = 18 feet)

REGR = 1.254 - 0.094(MF) - 0.077(CO) - 0.044(CG) - 0.042(TM)

<u>Altitude</u> <u>Error:</u>

MEAN = 1.567 (log RMS error in feet; hence, RMSE = 37 feet)

REGR = 1.567 + 0.061(GR) - 0.057(CO) + 0.051(PT x IP) + 0.043(IP)
+ 0.037(TM x PO x MF) - 0.035(TM x PO) + 0.031(3FIs)
+ 0.035(3FIs)

---

contrast must be multiplied by the position in Yates' standard order associated with each effect. The rule for multipling is as follows: multiply terms but drop all resulting squared terms. The remaining term represents a position in Yates' standard order where confounding exists.

For example, tracking mode (TM) is associated with position "af" in Yates' standard order (Table 9). Thus, "af" is multiplied by the defining contrast "abceg," with the result "bcefg." This is repeated for all three defining contrasts to determine confounding (Simon, 1973). However, because this design is a resolution V fractional factorial, it is already known that main effects are clean of confounding from anything less than a fourth-order interaction (this can be confirmed using the above method). However, second-order interactions are confounded with some third-order interactions. Normally one would not be too concerned here, but considering the three-factor interactions that were found significant, some caution should be used when interpreting those interactions.

TABLE 9

DIRECTION AND POSITION OF EACH MAIN EFFECT IN YATES' STANDARD ORDER

Design Label	Main Effect	Direction	Position in Yates' Order
a	TM	(-)	af
b	PT	(+)	abe
c	PO	(-)	abdf
d	MF	(-)	bdef
e	CG	(-)	bcef
f	CO	(-)	acef
g	GR	(+)	abcdf
h	IP	(+)	acdef

Center Point Test of Nonlinearity

As a gross test for nonlinearity, the grand means of crosscourse, alongcourse, and altitude tracking errors were contrasted with the respective means for the centerpoint conditions. A summary of the center point data is provided in Table 10. The crosscourse grand mean was 8% greater than the mean for its central conditions, for alongcourse 13% greater, and for altitude 11% greater.

TABLE 10

SUMMARY OF CENTER POINT MEAN RMS ERRORS IN FEET FOR EACH PERFORMANCE MEASURE

	Crosscourse Error	Alongcourse Error	Altitude Error
64 conditions	14.04	17.97	36.92
Center point	12.86	15.72	32.98
Difference	1.18	2.25	3.94

DISCUSSION

The purpose of the overall research effort is the optimization of both forward-looking and downward-looking tactical situation displays for all-weather instrument flight in VTOL aircraft. The present study represents the initial investigation critical to the downward-looking (HOVERING) display and control system. One ultimate purpose is the optimization of this portion of the overall system for each of several possible mission scenarios. However, optimization of the system would be prohibitive without first conducting screening experiments to identify critical design variables for various representative vertical and translational mission maneuvers. Those variables having important effects will be included in subsequent experiments to optimize display and control system design.

Position Error Magnification

The magnification factor of the vernier deviation indicator has had the single largest effect in the experiments conducted to date. For alongcourse and crosscourse tracking, MF accounted for at least 25% of the observed variance. As expected the higher magnification allowed more accurate tracking; it decreased both alongcourse and crosscourse tracking error by approximately 35%. This finding is consistent with the results obtained with the so-called Dukes display now in use by the U S Army; as magnification increased, tracking error decreased. Generally, if the scale factor of an error indication is increased, more precise control is possible. However, another problem appears as the magnification increases. To maintain an acceptable control/display ratio, control gain must be reduced to compensate for increasing display magnification.

The magnification values chosen for this initial screening experiment were in a range that is relatively robust with respect to the control/display ratio problem. However, certain mission phases may require tracking in the one-foot RMS error range. Testing during the initial development of the HOVERING system indicated that tracking errors could be reduced to less than a 0.01-foot RMS error. This was accomplished by increasing the magnification factor while concomitantly reducing translational control gain to maintain an acceptable control/display ratio. Reducing control gain can be operationally unacceptable in those cases in which the pilot must have immediate access to maximum dynamic responses. To accomplish the gain reduction without trading off vehicle responsiveness, the translational rate-hold function with lower-gain acceleration control (a mode that can be aborted) was used.

Control Order

Control order was also found to have a large effect on tracking error. For both alongcourse and altitude tracking, it accounted for approximately 15% of the observed variance. As the acceleration (second-order) control component was increased, RMS error was decreased by as much as 29% for alongcourse tracking and 23% for altitude tracking. Control order has been shown to be important across a variety of tracking tasks, but there is little consistency in published results (Chernikoff, Duey, and Taylor, 1960; Poulton,

1967, 1974; Roscoe, 1980; Roscoe and Kraus, 1973; Simon and Roscoe, 1981; Warner et al., 1976; Ziegler, 1968). In some cases first-order control was shown superior, while in other situations second-order control was more effective. It is unclear whether the present finding will hold across other mission phases, but it is clear that control order is an important design variable for optimization of any display and control system.

Prediction Time

Prediction time was found to be important for crosscourse tracking; as prediction time increased, tracking errors were reduced by 25%. Prediction time has been shown to be an important system variable, but the results are inconsistent. While some have shown longer times as more desirable, an equal body of research indicates that shorter ones are preferable (Bernotat and Widlock, 1966; Dukes, 1969; Gottsdanker, 1956; Kelley, 1962; Poulton, 1957; Roscoe, 1980; Smith and Kennedy, 1976; Weller, 1979). Prediction time is an important variable, but its appropriate level likely depends on the specific task or mission phase. Consequently, it must be included in future experiments involving maneuvers representative of a wide variety of operations.

The results of such experiments will make it possible to optimize the system across a variety of mission scenarios. It is not likely that there will be one "optimum prediction time," and therefore one of two alternatives must be chosen: either use a middle-of-the-road value that is best overall, with consequent performance compromises, or incorporate a computer algorithm that changes prediction time dynamically with changes in mission phase. The latter option is more difficult but far more desirable and will be looked at closely for future applications (this same logic may be applied to other display variables).

Control Gain

The vertical gain reduction logic accounted for nearly 14% of the observed variance in the altitude tracking task. The 41% reduction factor decreased altitude tracking errors by 23%. There are no comparable data to support this result directly, but it is known that control/display ratios must not be unreasonable (i.e., too sensitive or too insensitive). Unfortunately, the manner in which the vertical gain reduction was implemented did reduce pilot's control authority. This result points out the importance of finding an alternative implementation logic as in the case of the translational control with high display magnification. Analogously this problem may be overcome by adapting the vertical rate-hold function.

Control gain was also an important variable with respect to alongcourse tracking error. However, as with the vertical control, altering gain by limiting the vehicle's dynamic reponse is generally unacceptable (with the exception of limiting the G-force potentials), and further consideration must be given to integrating control system rules that maintain a more acceptable control/display ratio while maintaining full control authority. Using the rate-hold function may be the best solution to the translational control problem, but further development and testing will be necessary to assure optimum solutions to both the translational and vertical flight control problems.

Tracking Mode

Tracking was significantly improved when the tracking mode was set at roughly 50% vehicle-referenced compensatory and 50% target-referenced compensatory. In combination with the frequency-separated characteristics of the flight-path predictor, the 50/50 tracking mode becomes in effect a quasi-pursuit presentation. There is an enormous body of research that clearly demonstrates superior tracking with pursuit displays over compensatory presentations (Poulton, 1974). The quasi-pursuit presentation is of interest for two reasons. First and most obvious, this mode reduced alongcourse tracking error by 19%. Second, there are practical problems that arise in an operational system when a pursuit presentation is attempted.

By definition, a pursuit display is one that presents movements of a vehicle (or cursor) independent of the position of some target symbol. Consequently, both the target and the vehicle may position themselves near one edge of the display. For example, if both the vehicle and the target were displayed near the top edge of the display, then there is a considerable reduction in the relevant portion of the big picture displayed to the pilot. Also, the symbols can move off the display. To counter this problem the display can be scaled logarithmically, but this is generally undesirable. Such scaling alters the control/display ratio across the display, thereby making the display too sensitive near the center and too insensitive near the outer portion.

The quasi-pursuit presentation has the characteristic trackability of the pursuit presentation without the usual drawbacks. In the 50/50 tracking mode, both symbols are positioned relative to the center of the display. Thus, the target and the vehicle symbols are displaced proportionally from the center of the display to indicate direction and magnitude of error. This allows the most useful presentation of planning as well as tracking information in an integrated fashion; both the big picture and the tracking indications are referenced at the center of the display.

Important Interactions

There were several interactions and strings of interactions found significant for altitude tracking. More interesting than the effects themselves was the fact that the variables involved in the interactions are variables that do not directly affect the display of altitude information. Evidently, the pilot's ability to time-share the altitude and translational tasks was affected by the characteristics of the translational variables. It is likely that some salient features of the translational task allow better peripheral monitoring of the altitude task. These effects were not at all anticipated and must be investigated further.

The strings of three-factor interactions that were significant cannot be separated without the collection of additional data. However, it is evident that certain changes must be incorporated in the HOVERING system, so additional data collection would be inappropriate until these changes have been worked out. It is clear that a predictor must be included in the altitude presentation. Incorporation of a vertical flight-path predictor could shift many of the effects found significant in this initial

investigation. Also, reconsideration of control gain and the control/display ratio problem warrrants further investigation at the screening level before undertaking the optimization experiments.

Central Data Points

It appears from the results presented in Table 10 that there may be a slight bow in the response surface. However, the extent of the nonlinearity does not appear too severe. Some reconsideration of variable scaling will be required before further experiments are conducted. If the adjustments in variable scaling do not improve the linearity of the data in future experiments, then additional data points will be included in the basic experimental design to describe the nonlinear response surface. Nevertheless, the effects of the significant variables in this experiment were sufficiently linear over the ranges tested to warrant plotting them as shown in Appendix B.

PROSPECTUS

The HOVERING display and control system represents a positive step toward all-weather flight capability in VTOL aircraft. This has been accomplished by the integration of several basic display principles coupled with a considerable increase in control augmentation. This experiment isolated several of the critical system variables that will require optimization in future work. Optimization of the downward-looking HOVERING display and control system combined with the final development of the forward-looking (contact analog) display should allow stable, accurate, and safe operation of VTOL aircraft in zero visibility conditions. The remainder of this report will review the general concept of control augmentation, shortcomings of this initial experiment, and areas requiring future research and development.

Control Augmentation

In the context of this report, the term "control augmentation" has been used to refer both to the reduction in control order and to inertial stabilization of the vehicle to counter vehicle movements not called for by control inputs. In general, higher orders of control (those greater than second-order) should be allocated to onboard processors leaving the pilot responsible for lower control orders. There is an abundance of research that supports this principle. In the HOVERING system, the pilot's authority was maintained between first- and second-order control. This reduction in control order is not an unreasonable design feature with the current state-of-the-art.

Inertial counteraction of vehicle accelerations not called for by the control system is also not an unreasonable design requirement. In a report prepared for AVRADCOM (1980), specifications for the advanced scout helicopter included both a heading-hold function and a hovering flight mode. Augmentations of aircraft control systems that counter inputs to the system not called for by the pilot are quickly becoming a reality at an operational level. In the HOVERING system, longitudinal, lateral, and vertical accelerations as well as heading were all stabilized in the simulated vehicle model. Some worry that too much control authority is lost in systems of this sort, but a great deal of "flyability" is gained with a concomitant reduction in training requirements.

Shortcomings of this Experiment

On the whole this initial investigation was a success, but several improvements would be desirable in future research:

First, the proportion of variance accounted for by the experimental effects, while greater than normally reported, was below our expectations. Those effects determined to be real accounted for approximately 50% of the variance. A model derived from these data (recall Table 8) would not predict future performance in a VTOL simulator as accurately as one might desire. We expect that future investigations will account for at least 75% of the observed variance.

Second, no attempt was made at integrating relevant sidetasks into this initial investigation. Such tasks are the rule rather than the exception in an operational system. The incorporation of a reasonable sidetask into the next experiment should be considered.

Third, at some point in the ongoing program subjects from the population of interest must be tested to assess the generalizibility of results. The data from this experiment are not necessarily generalizable to Navy VTOL pilots.

Finally, a method is needed for including several mission phases as experimental variables in an economical manner. Inclusion of a wide variety of mission phases in an economical way can be difficult. Variables of this sort are usually qualitative and therefore uneconomical. Overcoming this problem will require the dimensionalization of flight-task demands into several continuous variables. If this can be done in a meaningful way then economical study of a variety of possible mission phases will be feasible.

Future Research and Development

There are a few augmentations that should be included in the HOVERING display. A vertical flight-path predictor is needed. This need will likely become even more apparent when more demanding vertical control tasks such as terrain following are introduced. Work is currently underway to augment the vertical flight information with a predictor. As was the case with the translational flight-path predictor, several additional variables will now require testing. Prediction order and prediction time of the vertical flight-path predictor will require testing across a variety of mission phases. As previously mentioned, augmentations of this sort make it necessary to continue research at the screening level before proceeding with experiments designed to optimize the HOVERING system.

Maintaining an acceptable control/display ratio without compromising control authority is also a problem. Maintaining a reasonable control/display ratio necessarily involves varying control gain. To do this involves limiting a pilot's control authority in some way. A limited authority mode that can be instantly aborted would appear to be a promising candidate. Adapting a rate-hold function by the addition of scaled down vernier acceleration inputs has been the option tested to date. Engaging the rate-hold mode has two effects: First, it serves to hold constant the vehicle's velocities at the time of engagement. Second, after the rate-hold mode is engaged, the control stick becomes a "fine-tune" control that allows small acceleration inputs to null position and rate errors.

This is accomplished by converting the control system to second-order control while also reducing gain (the specific reduction is dependent on the current MF level). A more complex implementation of this method could solve the control/display ratio problem while still maintaining a pilot's ability to assume full control authority at any moment. For example, as minimizing tracking error becomes essential for mission success (e.g., in the approach to a shipboard landing), the display can be augmented with software that dynamically increases display magnification while concomitantly reducing the control gain. If properly employed, such a control system logic could

function without any increase in pilot workload even though a high degree of tracking accuracy is achieved.

Programming dynamic changes in display configuration may ultimately be applied to other variables in addition to scale factors. As one example, prediction time is a strong candidate. As mission phases change, optimum prediction times vary. They also depend on the current prediction order and display magnification factor. With such complexities, system designers often choose either fixed parameters that provide acceptable but not optimum performance or the integration of manually selectable modes. Evidently the interrelationships among display variables are too complex for independent selection of variable levels in real-time operations. Consequently, programming a system to select optimum display configurations automatically for various mission phases should prove fruitful.

APPENDIX A

The vehicle being modeled has four degrees of freedom in the lateral, fore/aft, vertical, and azimuthal directions. The bank of the vehicle is always zero, as is the pitch. The vehicle is outfitted with thrust devices aligned with the three orthogonal body axes. There is also a device for applying torque around the vertical axis. All these power devices are independent of each other and may all be maximum simultaneously. The limits of these power devices are constant.

The operator controls these degrees of freedom with a right hand stick with three degrees of freedom and a left hand stick with one. Motion in the lateral direction is controlled by a left-right motion of the right hand stick around a pivot below the hand. This stick motion is used to control the thrust on the left-right body axis. Motion in the fore/aft direction is controlled by rotation of the right stick hand grip around a horizontal axis through the palm roughly perpendicular to the forearm. This rotation causes the top of the handle to move roughly forward and backward. This stick motion is used to control the thrust along the fore/aft axis of the vehicle.

The motion in the vertical direction is controlled by an up-down motion of the left stick around a pivot behind the operator's hand. This stick motion is used to control the vertical thrust. Finally, the azimuthal motion is controlled by a twisting of the right stick handle around a roughly vertical axis passing through the handle. This stick motion is used to control the torque applied to a rotating platform on which the sticks and operator sit.

The phrase "is used to control" above covers a complicated operation. Each of the four degrees of freedom may be varied independently of the others between first- and second-order command. This means the stick position can be a velocity command or an acceleration command or any fractional mix of the two. The actual velocity is compared to the commanded velocity and a velocity error signal is developed. The actual acceleration is compared to the commanded acceleration and an acceleration error signal is developed and integrated.

The velocity error and the integrated acceleration error are combined in whatever mix is specified to produce a commanded acceleration signal. It is this signal which is limited before being summed with the drag acceleration and integrated to yield actual velocity and (following a second integration) actual position. Drag is computed by squaring the actual velocity and used to reduce the magnitude of the limited acceleration. The effect of this last computation is to produce terminal velocities for the vehicle in all four degrees of motion at which full power is cancelled by the the drag to produce a steady velocity.

The azimuth system is more complex than the three translational systems. The vehicle azimuth angle is the sum of two angles. The first is the angle of the platform to which the vertical tail fin is attached displaced from the vehicle center of mass. This fin is an air foil in the horizontal wind due to translational velocities. It has lift which increases with angle of attack up

to a stall. Its drag is the sum of a term proportional to the square of lift and another term proportional to its projected area. This fin produces a torque which acts to drive the sideslip angle to zero or align the center-of-mass-to-fin axis with the wind.

By itself this proved inadequate, since at zero slip angle there was no reason for the platform to stop moving and its momentum carried it through to the other side where again the torque drove it back to and through zero slip angle. The damping due to drag did decrease the maximum excursion from one cycle to the next, but an additional element was required for increased damping constant. This azimuthal stability augmentation system consists of torque applied to slow the rotation rate whenever the slip angle is moving to zero. The magnitude of the torque is proportional to the angular velocity and inversely proportional to the magnitude of the slip angle plus a small constant.

The second angular component to vehicle azimuth is a commanded azimuth angle computed from the stick in much the same manner as the three translational positions. This angle is not influenced by any translational vehicle velocities. Thus it may be thought of as the angle with respect to the first platform of a second platform with cylindrical symmetry around a vertical axis, which is controlled by the operator with limited torque and with drag depending on its angular velocity with respect to the first platform. The operator is also on this platform and his viewing direction is determined by it. The vertical fin, although carried by the first platform and acting on it as described above is always behind the operator. Thus what the operator does with his platform changes the position of the fin on the other platform.

What is the benefit of this complexity? First consider the case of hover. The operator is free to command the second platform (essentially the vehicle) to any azimuth desired. The vertical fin is always behind the operator. The fore/aft and lateral vehicle axes are in fixed relationship to the operator and the control stick motions. In the absence of any horizontal motion there are no forces on the vertical fin and thus no rotation of the first platform.

Second, consider the case of rapid horizontal motion with no commanded change in the second platform angle. Any sideslip will produce a torque on the first platform, and it will turn into the wind carrying the second platform with it. In the event that the operator is calling for a steady lateral motion, this will result in a steady turn rate. Thus even though the operator is not commanding any turn, by flying the vehicle into continual sideslip a turn results from the vehicle aerodynamics.

At low speeds the lift and drag of the vertical fin are slight, so the vehicle may be manuevered for/aft and left/right freely without producing rapid rotations of the first platform. Only those rotations commanded by the operator on the second platform alter heading. At higher speeds the operator still has the ability to rotate the vehicle into any sideslip angle desired and can hold heading by applying angular velocity to his platform just sufficient to balance the angular rate in the opposite direction induced on the first platform by the vertical tail.

There are two special modes for the vertical motion control. The first is an altitude-hold mode, which is entered anytime the stick is centered and the vertical velocity magnitude is less than a threshold amount. When the altitude-hold mode is in effect, the model maintains the altitude at the value it had when the mode was activated. The velocity threshold is set at .3 ft/sec. This mode is redundant when the stick position calls for a pure velocity command. The second mode is called vertical velocity-hold mode and is entered when a button on the left stick is pressed.

In the vertical velocity-hold mode the stick position (when the mode was entered) is remembered and used as a velocity command to the vehicle in place of the vertical stick. The vertical stick becomes a velocity controller for this remembered stick position, so if the operator holds the stick off center after entering the mode the remembered stick position slowly changes in the direction of the deflection. In addition the vertical stick becomes a decreased sensitivity acceleration command to the vehicle in whatever fraction acceleration command was originally present.

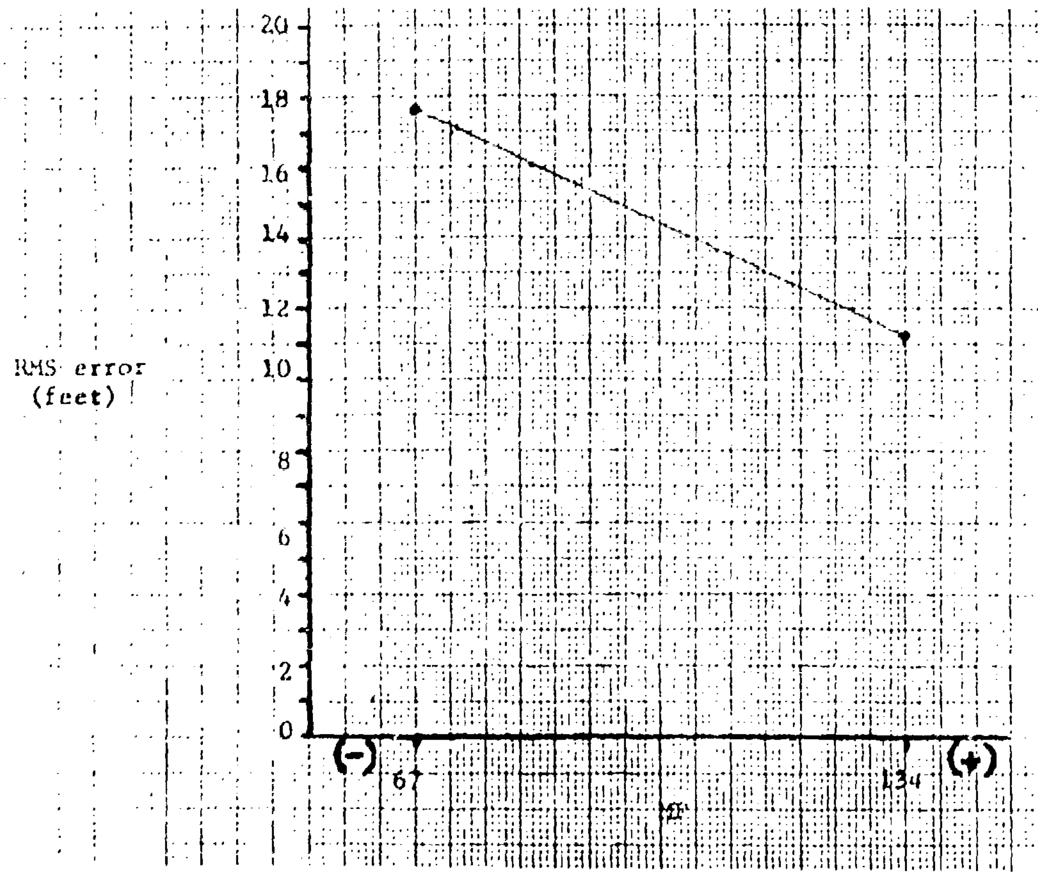
There is another complication of the vertical motion control system that divides the altitude range into a number of distinct regions. The lowest is from 0 to 60, feet and the second is from 60 to 250 feet. For each of these ranges there is a set of velocity and acceleration command gains for the stick. The ratio between the gain in one range and the gain in the next higher range is 0.545. It is not until the operator flies above 1000 feet that the vertical control has the gains specified as normal. At take off the stick sensitivity was multiplied by the cube of 0.545, resulting in only 16% of the normal value.

The two horizontal translational motions also have a velocity-hold mode that is entered or exited for both when a button on the right stick is pressed. It functions in the same manner as the vertical velocity-hold mode.

Graphical summary of important effects for each performance measure.*

Crosscourse Tracking Error:

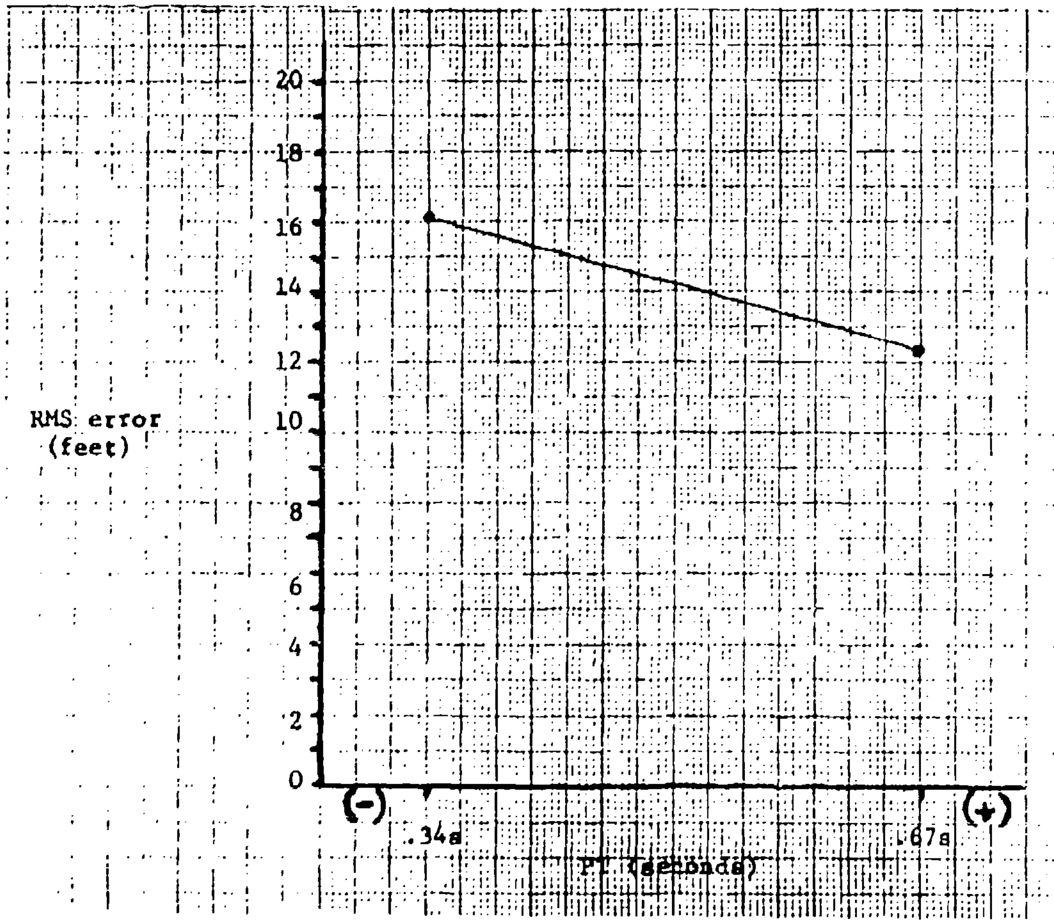
1. Magnification Factor (MF)



* Experimental center-point values showed slight departures from the linear relationships between the + and - factor levels shown in these graphs.

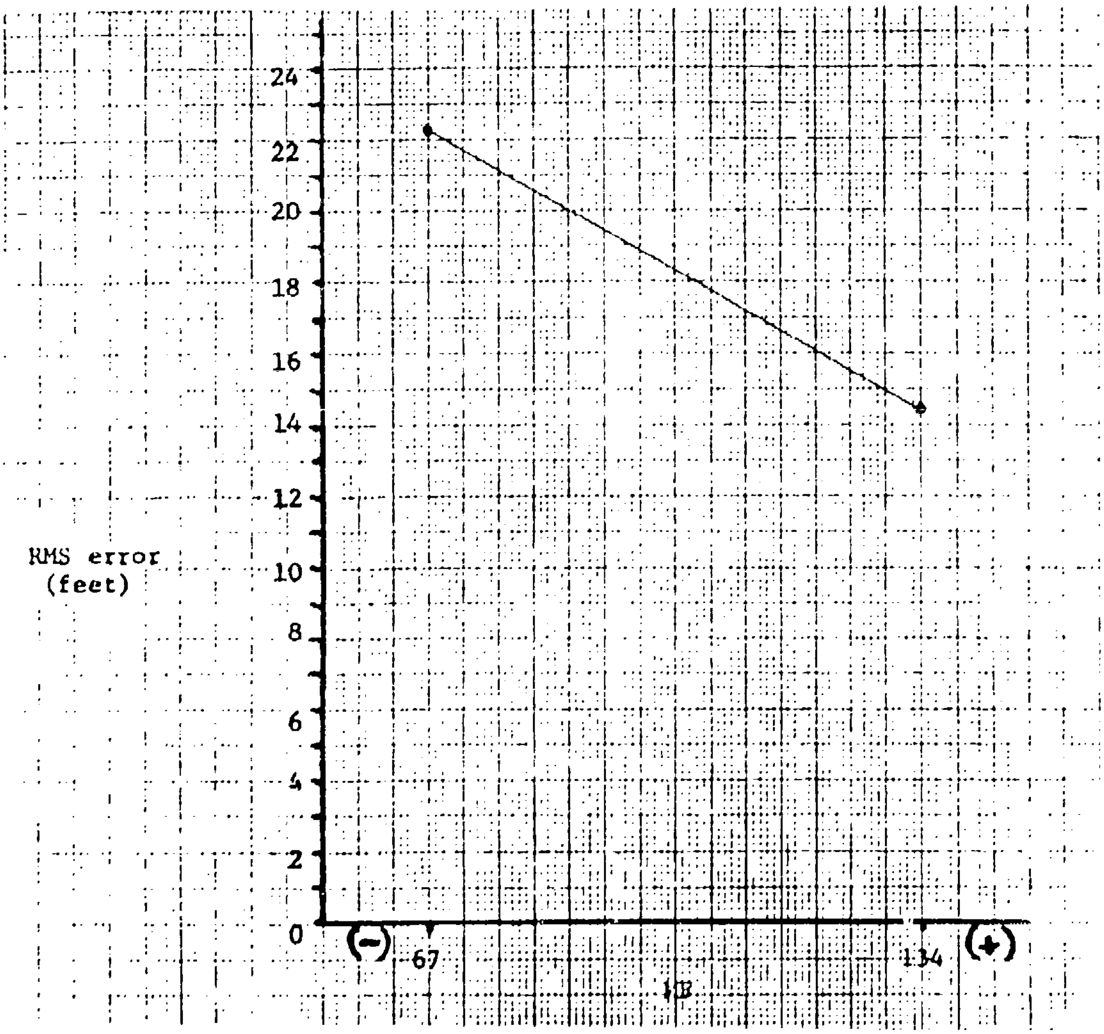
Crosscourse Tracking Error:

2. Prediction Time (PT)



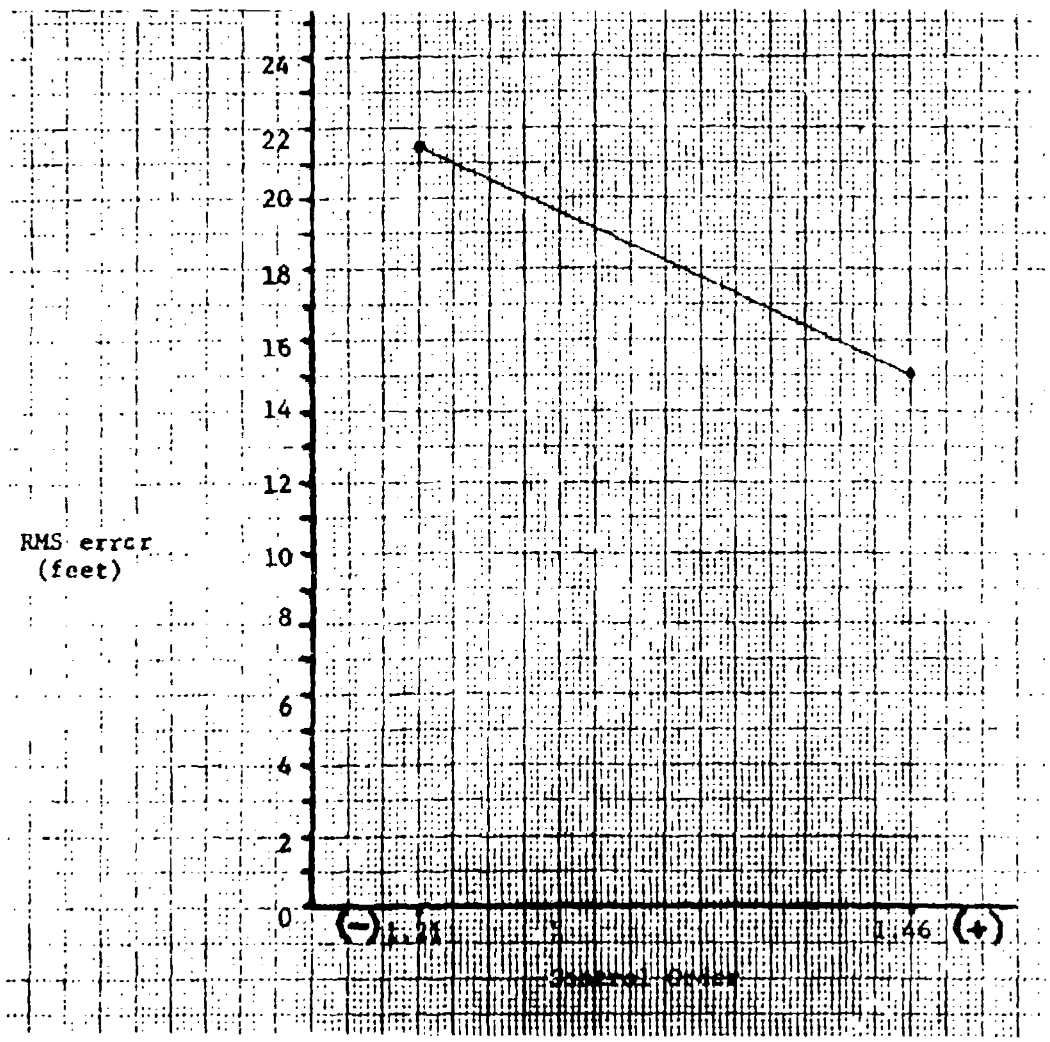
Alongcourse Tracking Error:

1. Magnification Factor (MF)



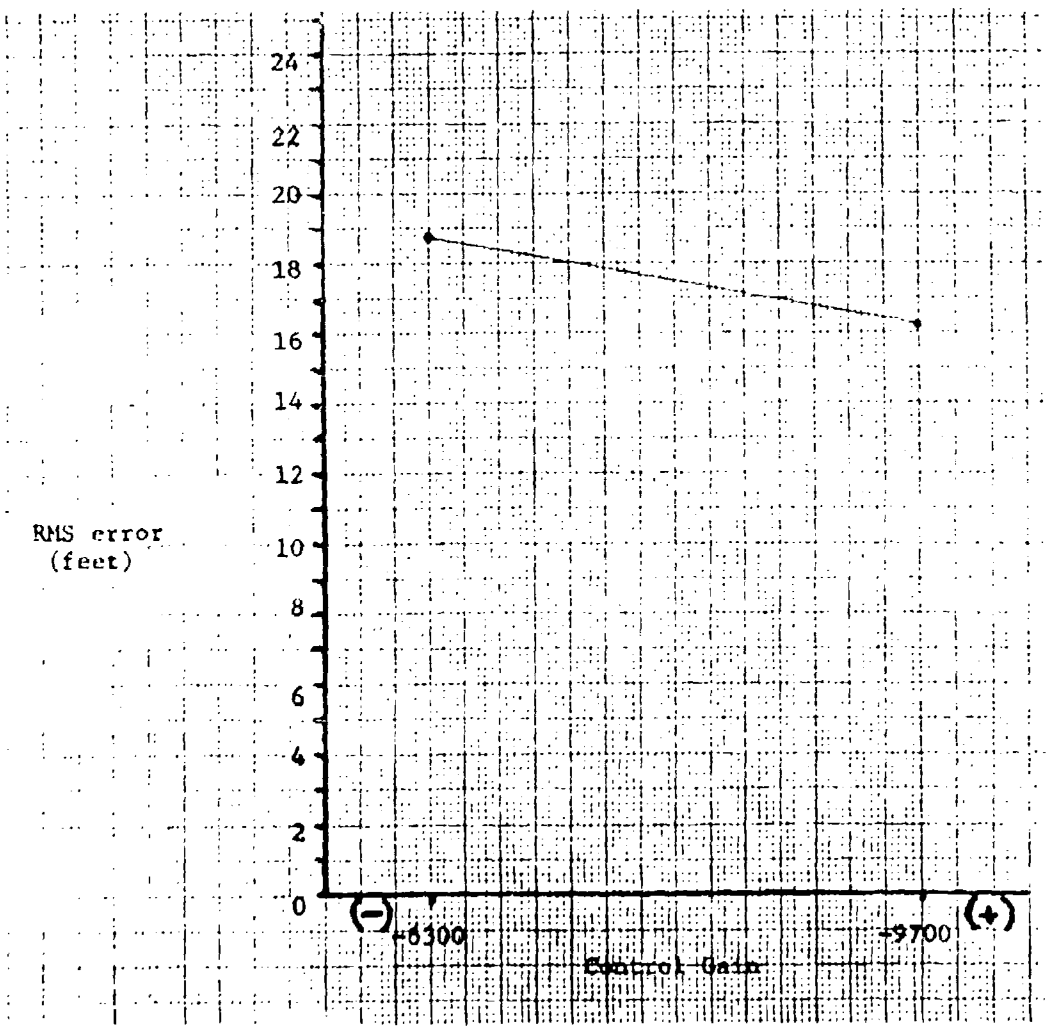
Alongcourse Tracking Error:

2. Control Order (CO)



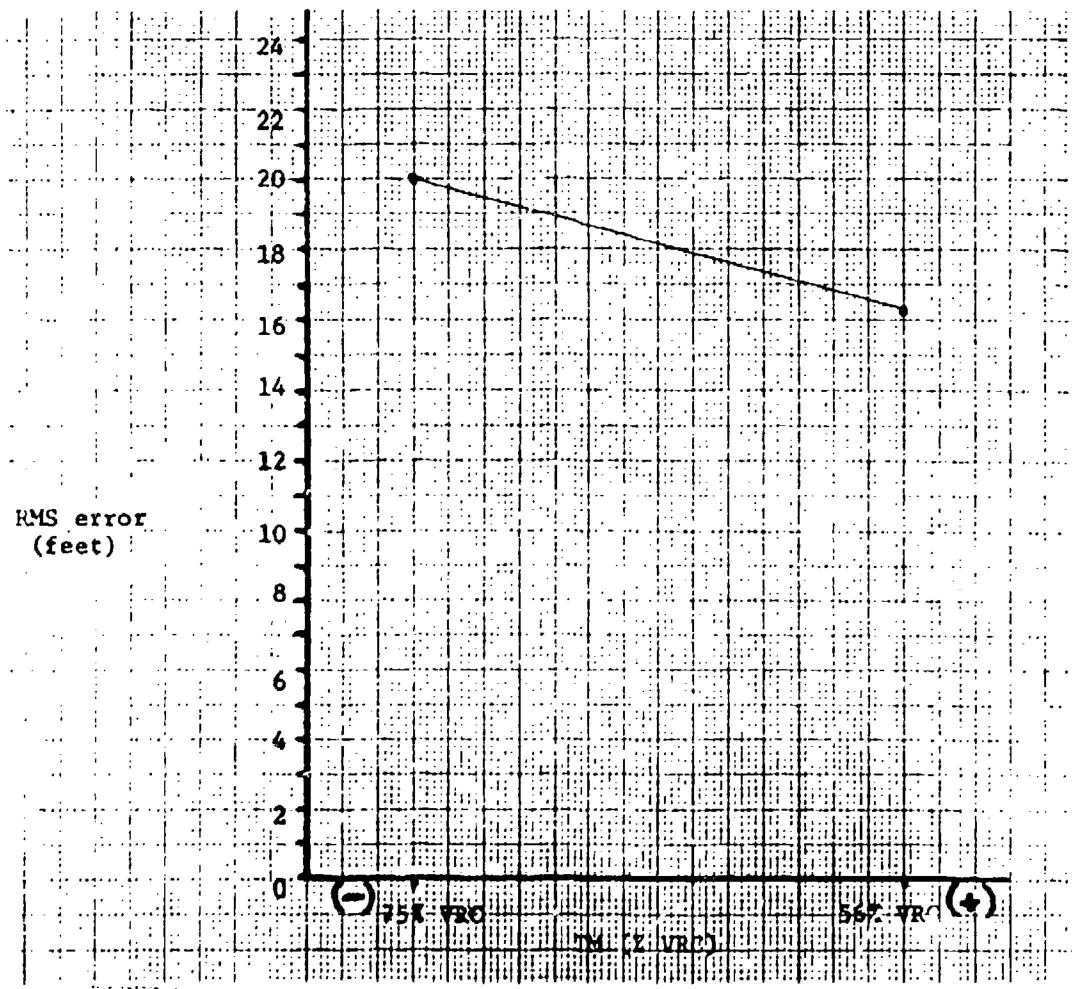
Alongcourse Tracking Error

3. Control Gain (CG)



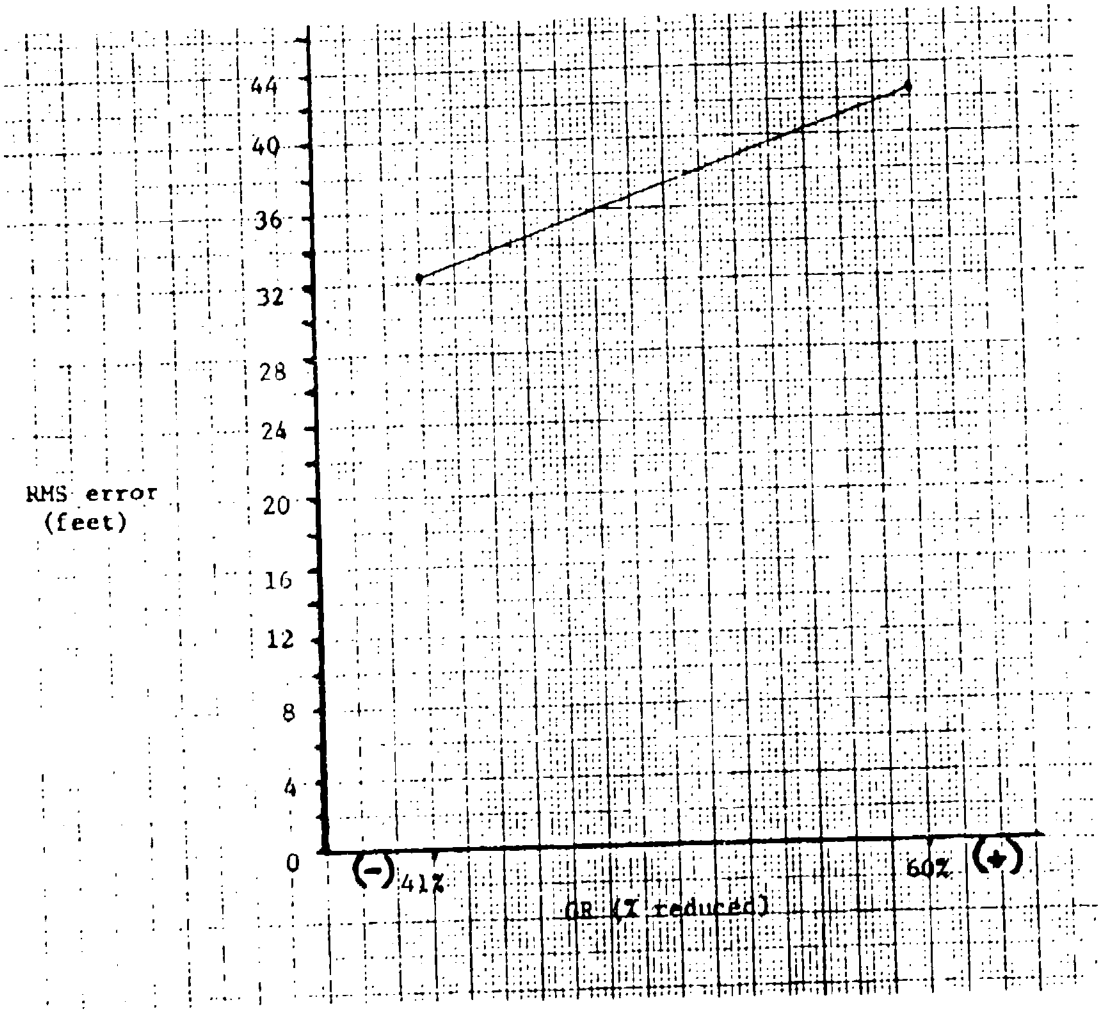
Alongcourse Tracking Error

4. Tracking Mode (TM)



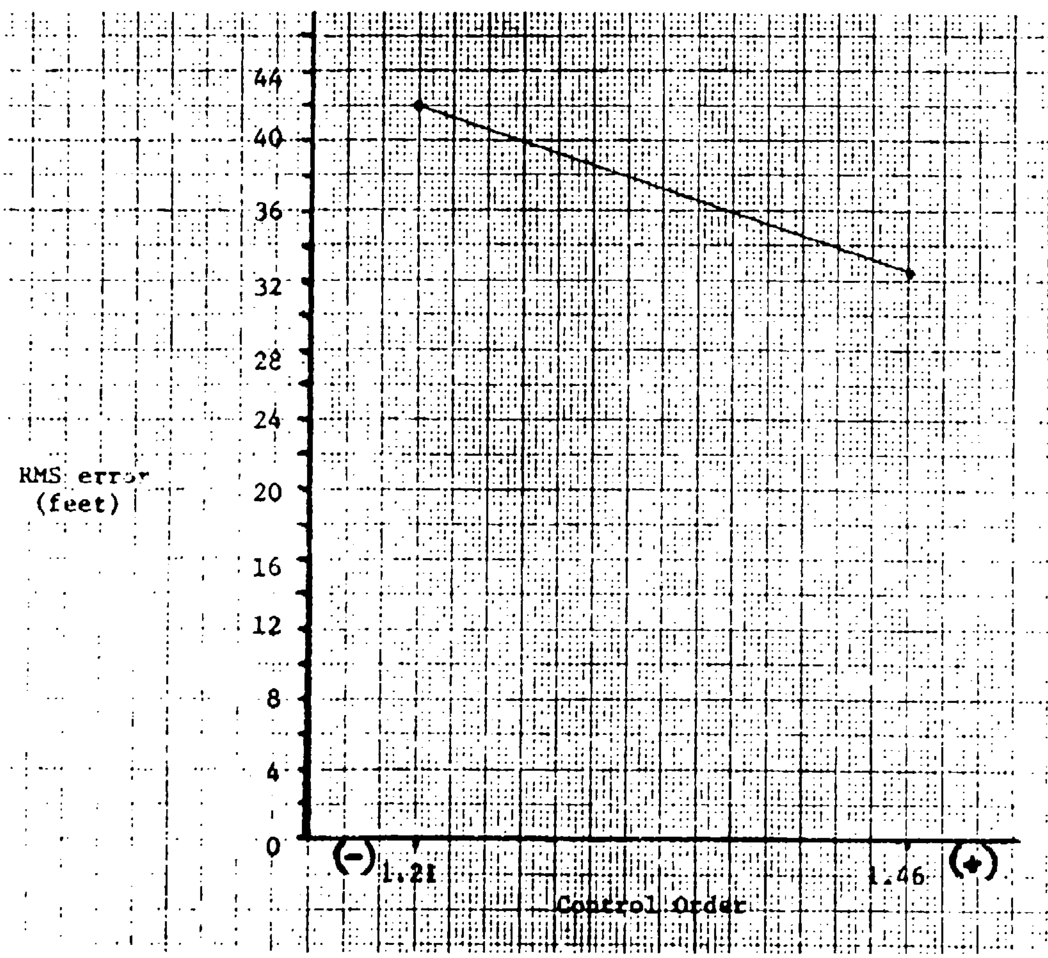
Altitude Tracking Error

1. Gain reduction logic (GR)



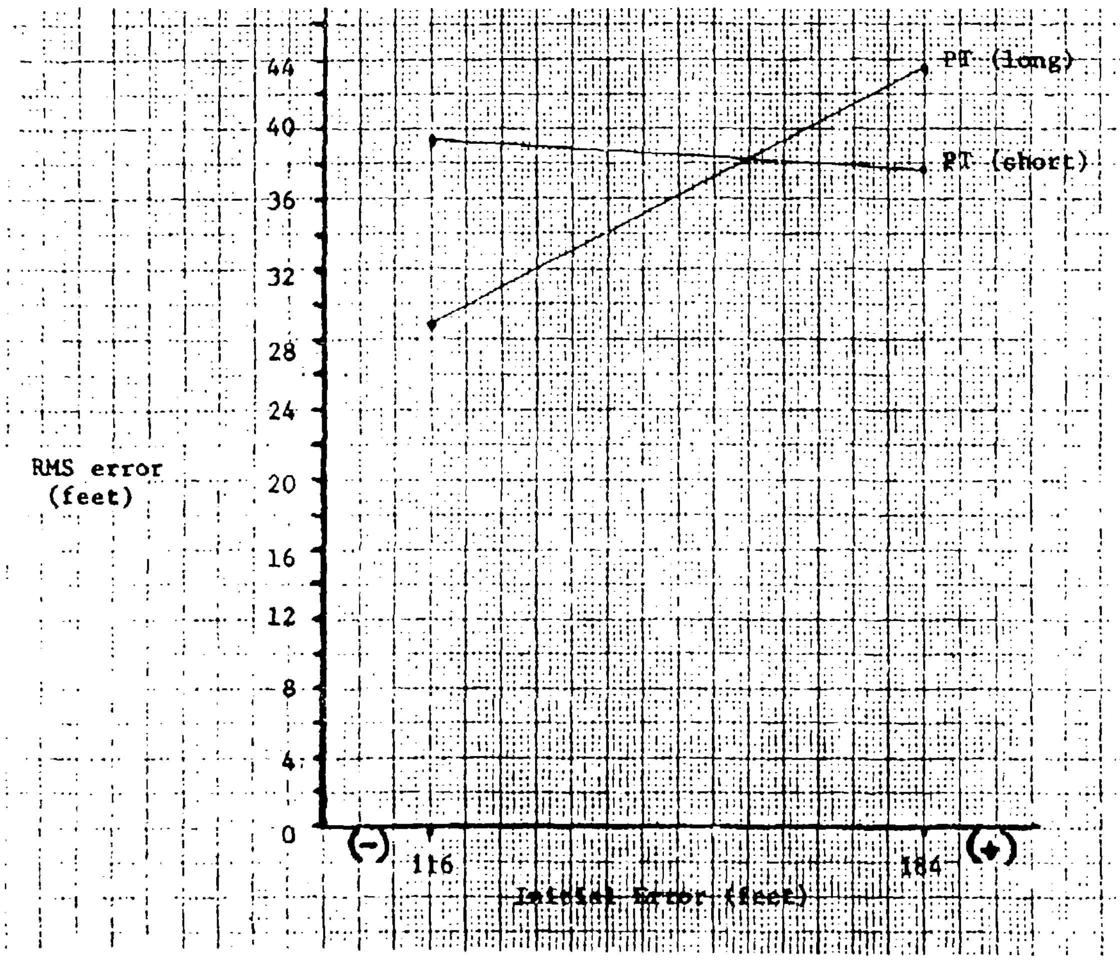
Altitude Tracking Error

2. Control Order (CO)



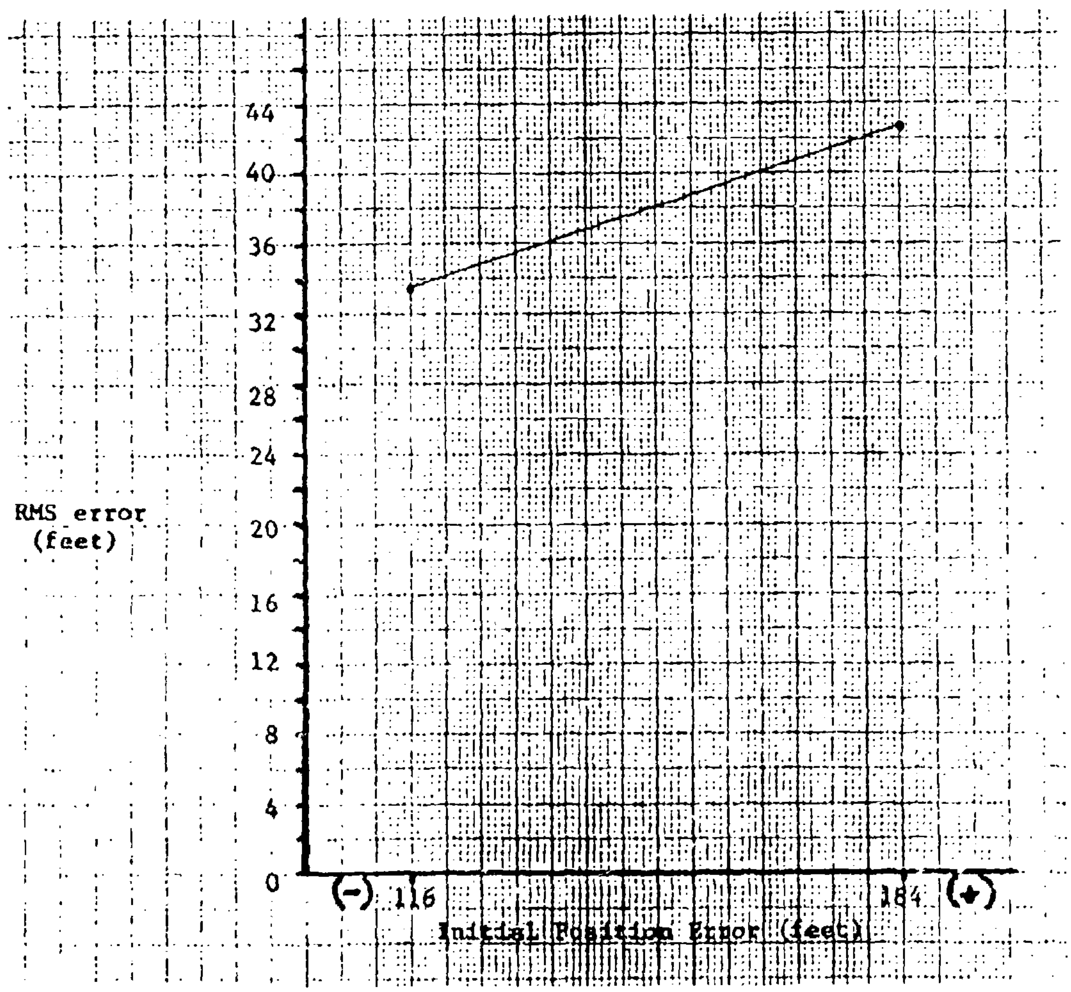
Altitude Tracking Error

3. Prediction time (PT) x Initial Position Error (IP)



Altitude Tracking Error

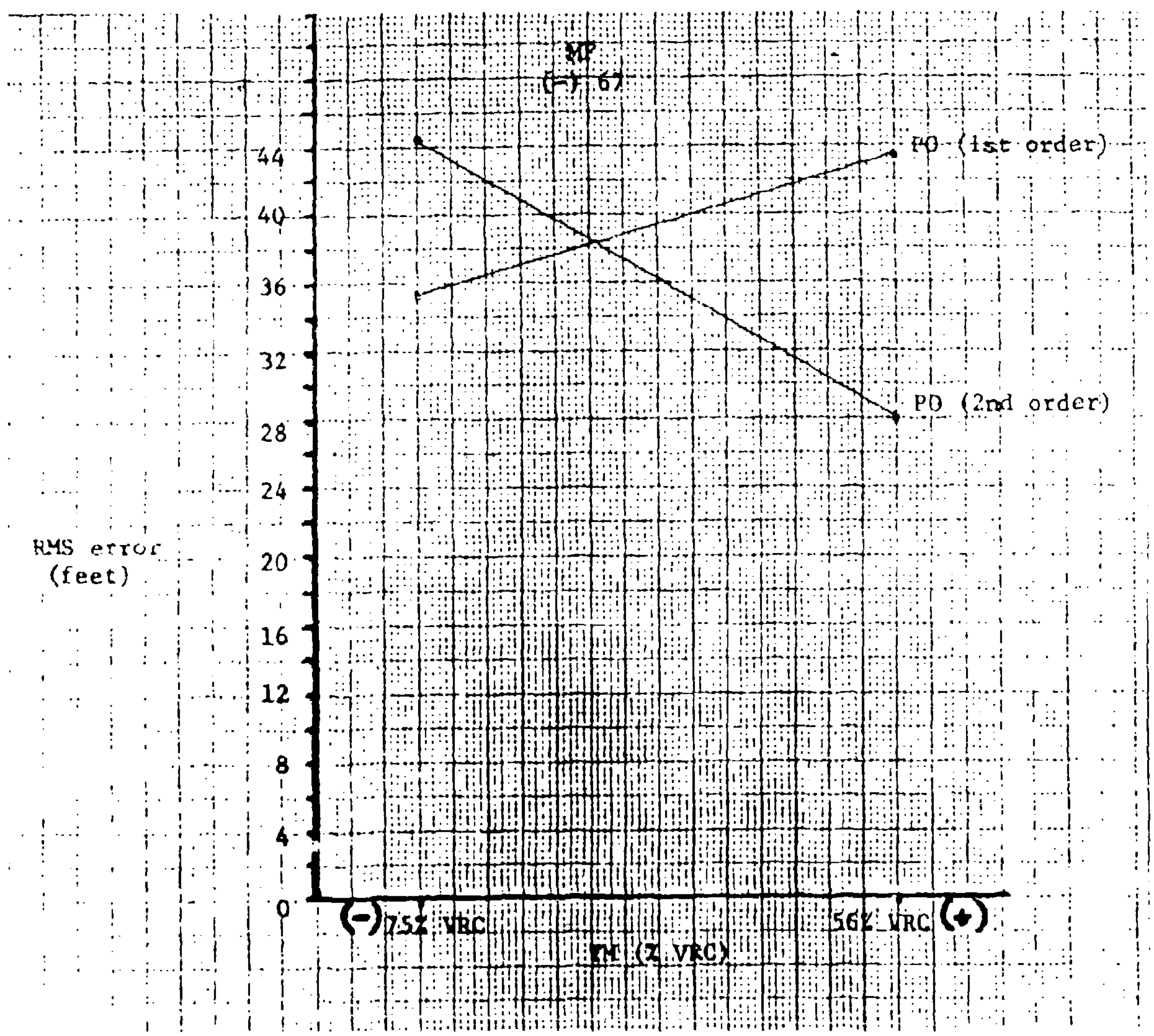
4. Initial Position Error (IP)



Altitude Tracking Error

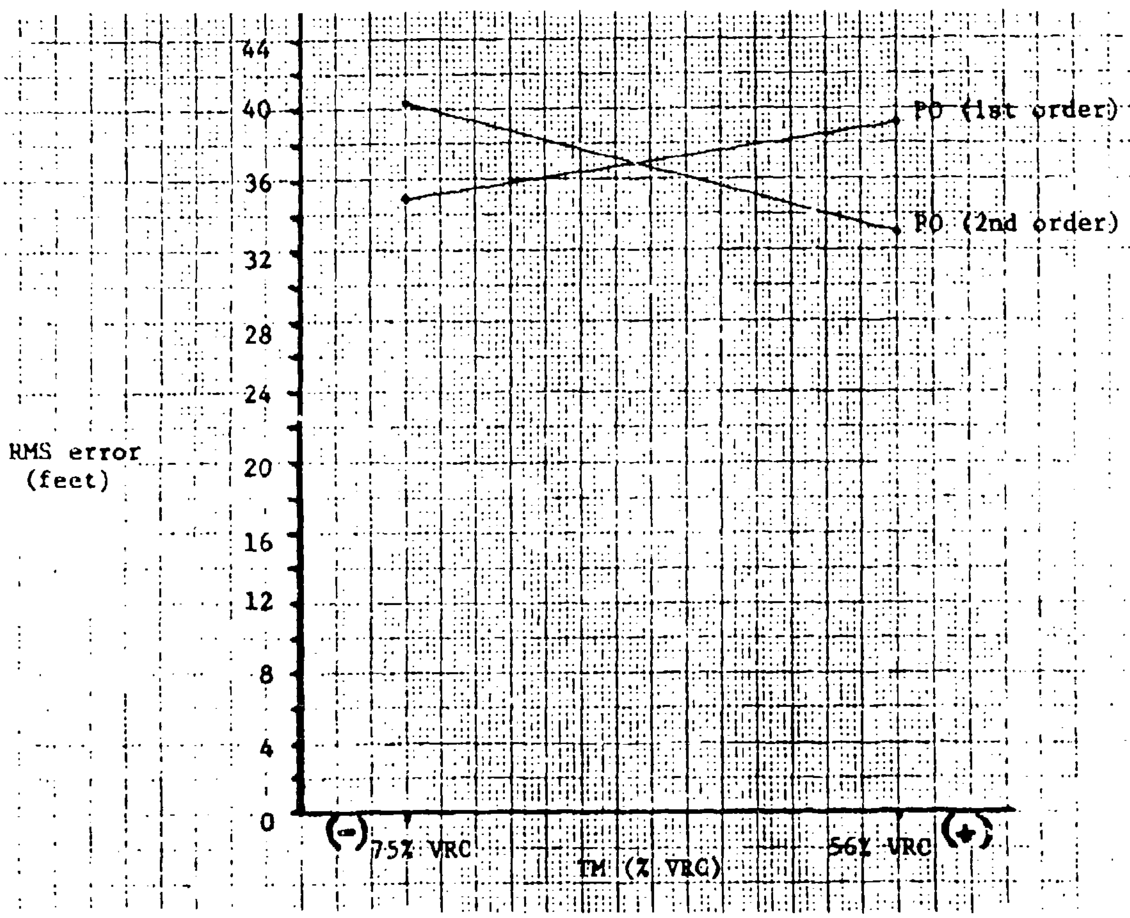
5. Tracking Mode (TM) x Prediction Order (PO) x Magnification Factor (MF)

(This graph represents TM x PO at the "-" level of MF, "+" level is on the next page)



Altitude Tracking Error

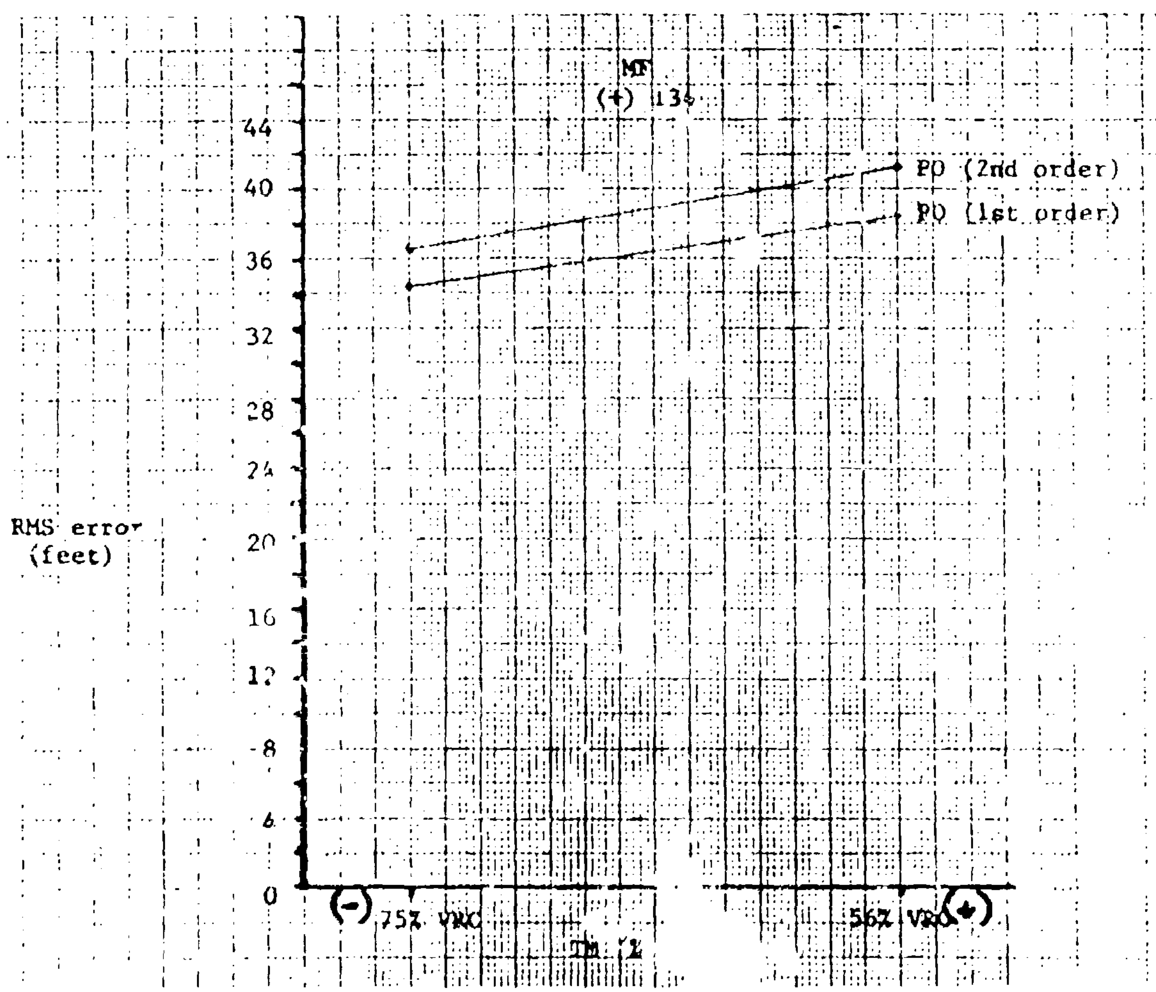
7. Tracking Mode (TM) x Prediction Order (PO)



Altitude Tracking Error

6. Tracking Mode (TM) x Prediction Order (PO) x Magnification Factor (MF)

(This grapn represents TM x PO at the "+" level of MF, "-" level is on previous page)



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